Universidade do Minho
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Design of Fibrous Structures for Civil Engineering Applications

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Resumo

Os recentes desenvolvimentos, ocorridos na tecnologia das fibras e nas estruturas fibrosas, permitiram produzir materiais fibrosos avançados para inúmeras aplicações não convencionais. O uso de materiais fibrosos como material de reforço de matrizes cimentícias é uma das aplicações que na última década tem sofrido vários desenvolvimentos. Devido à ausência de uma adequada resistência à tracção, os elementos de betão necessitam de reforço, de forma a maximizar a sua capacidade de fazer face às solicitações mecânicas. Um dos materiais mais utilizados para reforço do betão, é o aço, sendo por isso actualmente o mais aceite como forma de reforço. No entanto, devido à corrosão, fadiga e aos efeitos nefastos da presença de agentes agressivos, a rotura das estruturas de betão reforçadas com aço, é uma consequência inevitável. De forma a ultrapassar os problemas associados às estruturas de betão reforçadas com aço, nomeadamente o da corrosão, e simultaneamente melhorar e aumentar o tempo de vida útil das estruturas e a sua durabilidade, uma nova abordagem ao reforço do betão tem sido alvo de desenvolvimentos – *Textile Reinforced Concrete* (*TRC*) – betão reforçado com estruturas fibrosas. Assim, o TRC é um material de construção inovador no qual os materiais fibrosos são utilizados para reforçar matrizes cimentícias de forma a eliminar o problema da corrosão do aço e a fornecer a resistência à tracção adequada ao elemento de betão.

Neste contexto o principal objectivo deste trabalho é o desenvolvimento de estruturas fibrosas, nomeadamente estruturas fibrosas orientadas direccionalmente (EFOD) para aplicações na construção civil enquanto material de reforço de elementos leves de betão, substituindo o aço e ultrapassando a sua principal desvantagem – a corrosão. Foram desenvolvidas dez estruturas EFOD variando o reforço no sentido transversal e longitudinal. Lajes de betão auto-compactável foram reforçadas com as EFOD e ensaios de flexão foram realizados de forma a avaliar o seu desempenho mecânico e identificar a influência da massa linear (tex) e densidade estrutural dos reforços (mechas de fibras/cm) em estruturas abertas $0/90^0$. O comportamento mecânico das lajes reforçadas com as estruturas fibrosas foi comparado com o comportamento mecânico de lajes reforçadas com aço e com lajes sem reforço. Os resultados indicam que as EFOD melhoram o comportamento mecânico do betão à flexão. A massa linear e a densidade estrutural das mechas mostram ter uma influência significativa no comportamento mecânico do betão tendo sido possível estabelecer correlações interessantes entre estes factores e o desempenho mecânico no que se refere à absorção de energia em ensaio de flexão.

Palavras-chave: Compósitos; Estruturas fibrosas orientadas direccionalmente; Betão reforçado com estruturas fibrosas; Corrosão; Elementos leves de betão reforçado com estruturas fibrosas; Fibra de vidro.

ABSTRACT

As a synergy of fibre and fibrous structures technology developments, nowadays it is possible to produce advanced fibrous materials for many non-conventional applications. The use of fibrous materials as reinforcement materials of cementitious matrices is one of its many applications that have gain new developments over the last years. Due to its inherent low tensile strength, concrete requires reinforcement in applications where significant tensile stresses will be realized in order to maximize its load-carrying capability. Currently the most widely accepted form of reinforcement is welded-wire mesh (WWM) of steel. However, due to steel corrosion, fatigue and other degradation agents, failure of those reinforced concrete structures is an unavoidable consequence. Thus, the development of alternative materials to steel in concrete reinforcement has been a priority in the last decades. In order to overcome the problems associated to the steel reinforced concrete, namely corrosion and simultaneously improve the serviceability and performance durability of steel reinforced concrete structures a new approach to concrete reinforcement has been developed in the last years - *Textile Reinforced Concrete* (TRC). Thus, TRC is an innovative construction material where fibrous structures are used to reinforce cementitious matrices in order to eliminate the corrosion of steel reinforcement, providing adequate tensile strength to the concrete reinforced element.

In this context the main objective of the present work consisted in the development of fibrous structures, namely directionally oriented fibrous structures (DOFS) for civil construction as reinforcement material for lightweight concrete elements, replacing steel and overcoming it main drawback – corrosion. It was developed and produced ten different DOFS varying the transversal and longitudinal reinforcement. Self-compacting concrete slabs were reinforced with the DOFS and bending tests were carried out in order to evaluate their mechanical behaviour and identify the influence of linear density (tex) and structural density of the reinforcements (rovings/cm) in open $0/90^0$ structures. The mechanical behaviour of the reinforced concrete slabs were compared to that mechanical behaviour of steel reinforced concrete and also with slabs without any reinforcement. The results show that DOFS improve the bending mechanical behaviour. Either linear density or roving structural density has shown to have a significant influence on the reinforced concrete element energy absorption capacity in a different way and depending on the percentage of fibre. Correlations between these tow factors and energy absorption under bending test have been established.

Keywords: Composites; Directionally oriented fibrous structures; Concrete reinforced with fibrous structures; Corrosion; DOFS reinforced lightweight concrete elements; Glass fibre.

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CHAPTER I

INTRODUCTION

1.1. WORK SCOPE

With the advent of modern civilization and development of scientific knowledge, there has been an upsurge in demand for developing newer materials for non-conventional applications. In fact, with the technological recent breakthrough focus has been paid on developing specific materials to perform in stringent conditions such as, highly corrosive environment, high temperature and pressure, higher strength at low weight among others, where the conventional materials failed to service. Thus, engineered materials have been produced with highly specific properties according to the application needs/requirements. However, innovation was not only limited to developing materials with specific properties but it also addressed the production methods, improved processing techniques, effective use of energy while processing and with the least environmental impact. Advanced materials with combination of properties for specific end-uses became a reality.

Over the last decades composite materials, polymers and ceramics have been the dominant emerging materials. The volume and number of applications of composite materials has grown steadily, penetrating and conquering new markets. Modern composite materials constitute a significant proportion of the engineered materials market ranging from everyday products to sophisticated niche applications.

Today, high-performance fibre reinforced composites are starting to challenge conventional materials such as steel and aluminium in everyday applications like, medical devices and civil infrastructure. Continuous advances in the manufacturing technologies and performance of fibre reinforced composites have intensified the competition in a growing range of applications leading to significant growth in its market acceptance. For any given application and industry sector, the final choice is often a competitive outcome of alternative solutions, including advances in alternative materials. Each type of composite brings its own performance characteristics that are typically suited for specific applications. The development of a composite component involves both material and structural design. Unlike conventional materials, the properties of composite material can be designed according to the end use.

Increasingly enabled by the introduction of new type of fibres, fibrous materials have seen their application range increased for technical applications. In the past years several developments have been done on matrices reinforcement of different nature (cementitious, polymeric, among others), leading to composite materials reinforced by fibrous materials, namely due to their unique properties. Considering different textiles techniques it is possible to combine different features in one product like, flexibility, lightness, strength among others. Thus, high performance composites like textile reinforced composites or fibre reinforced composites can now be found in such wide range of applications as composite armouring.

Composites have long been used in building and construction industry. Concrete structures are constantly subjected to loads as well as to aggressive and degrading agents. These drawbacks lead to a poor mechanical performance, a limited service life and to a high rehabilitation maintenance costs. In the last years a new approach to concrete reinforcement has been developed in order to overcome reinforced concrete deterioration problems, improve the service life and improve reinforced concrete structures durability – *Textile Reinforced Concrete* (TRC) – an innovative material where fibrous structures are used as reinforcement material of concrete elements. TRC benefits of corrosion resistance and lightweight have proven to be attractive in many applications and presents large opportunities to be used as an alternative material to replace conventional materials such as, timber, steel and aluminium in buildings. Besides, TRC can provide an important contribution to the safe and economical use of resources.

1.2. WORK JUSTIFICATION

Concrete elements need to be reinforced due to a fundamental lack of adequate tensile strength. One of the most largely used reinforcement material for concrete elements is steel. Currently the most widely accepted form of reinforcement is welded-wire mesh (WWM), a mesh of small diameter steel rod that is placed in concrete. However, due to steel corrosion, fatigue and other degradation agents, failure of those reinforced concrete structures is an unavoidable consequence being this the main problem of building and civil industry. Therefore, steel as concrete reinforcement material, present three major drawbacks namely, corrosion, limited service life and high maintenance costs of the concrete structure. Thus, the development of alternative materials to steel in concrete reinforcement has become a priority. Alternative materials need to be developed to overcome the failure of building conventional materials namely due to corrosion but at the same time providing adequated mechanical resistance, at low costs.

An alternative material to steel, which is being used for some years, is fibrous materials. These materials find many applications in several fields and their use as randomly oriented fibres in concrete reinforcement is quite well understood and developed. However, the use of fibrous structures such as wovens, knits, braids and nonwovens, as reinforcement for cementitious composites, are a relatively new field for which some detailed research is needed. Moreover, the use of fibrous structures as a pre-stressing element is requiring additional knowledge. This may be confirmed by analysing the literature available showing just few works in this field and tremendous scientific and technical interest for new developments.

The present work intends to contribute to the development of new construction fibrous materials to replace steel in concrete reinforcement.

1.3. RESEARCH OBJECTIVES

This research work aims to develop of fibrous structures to be used as a concrete reinforcement material, in order to replace and avoid the main drawbacks of steel, corrosion. The directionally oriented fibrous structures (DOFS) developed will be able to compete with steel on the production of concrete lightweight elements. The influence on different fabric structural parameters on the mechanical properties of slabs reinforced by DOFS will be studied namely the roving linear density (tex) and roving structural density (rovings/cm).

1.4. METHODOLOGY

The selected methodology to undertake this work consisted in the following stages:

Objectives definition

The objectives were defined to contribute for the resolution of corrosion problems in concrete structures in building and civil industry through the development of alternative materials, in this case fibrous structures.

Literature survey

The literature survey was carried out in order to examine thoroughly the knowledge regarding to the type and application of fibrous materials and structures in concrete reinforcement. In addition, problems associated to the application of steel in concrete reinforcement have also been analysed.

Once defined the objectives and performed the literature survey to establish the state-of-the-art, the working plan for the present work was developed.

Working plan definition

Considering the critical analysis of the available information, the work was planned in order to achieve to the objectives proposed. Thus, the work is divided in three different stages.

In the first stage several directionally oriented fibrous structures were developed as well as the corresponding production technique. Ten different fibrous structures were produced with E-glass fibre varying the linear density (tex) and rovings structural density (rovings/cm).

The second stage is regarding to the characterization of directionally oriented fibrous structures and evaluation of their mechanical properties.

The third stage is related to the application of the developed directionally oriented fibrous structures to lightweight concrete slabs. Twelve different directionally oriented fibrous structures reinforced slabs were produced as well as a steel reinforced concrete slab for comparison. Bending tests were carried out and the results obtained were evaluated and compared in order to understand the influence of the linear density and rovings structural density on the bending mechanical performance.

Experimental work

The experimental work comprises the followings steps:

- technique development for the production of the directionally oriented fibrous structures;
- production of directionally orientated fibrous structures varying longitudinal and transversal reinforcement in terms of linear mass and density;
- characterization of directionally oriented fibrous structures and evaluation of their mechanical properties;
- production of directionally oriented fibrous structures reinforced concrete slabs and steel reinforced concrete slabs;

- evaluation and comparison of textile reinforced concrete slabs mechanical performance;
- evaluation and comparison of mechanical performance between textile reinforced concrete slabs with steel reinforced concrete slabs.

Results analysis

The results obtained in each stage of the work, were treated and analysed in order to verify the satisfaction level of the objectives initially proposed.

Conclusions and further work

The conclusions were obtained according to the results obtained and considering the initial proposed objectives. The experience acquired within this project will be used to define future research perspectives in this area.

1.5. THESIS STRUCTURE

The present thesis is comprised by five chapters including, introduction, conclusions and further work and the references, being organized according to the claimed objectives. A brief resume of each chapter of the thesis is presented as follows:

Chapter I – Introduction

In the first chapter are presented the objectives to be achieved, the work developed, the selected methodology, the justification for this work and the thesis structure.

Chapter II – State-of-the-Art

Chapter II describes the state-of-the-art regarding to technical textiles, composites materials reinforced by fibrous materials and fibrous structures and corresponding applications in building and civil engineering namely in concrete.

Chapter III – Development of directionally orientated fibrous structures (DOFS)

The present chapter describes the directionally oriented fibrous structures development which was used as concrete reinforcement material. It is described the experimental proceeding regarding to the directionally oriented fibrous structures production and respective characterization. Materials, equipments, tests and the results obtained as well as respective conclusions are presented.

Chapter IV – Application of directionally orientated fibrous structures (DOFS) in concrete slabs reinforcement

Chapter IV presents all the experimental procedure regarding to the production technique of lightweight concrete slabs reinforced with the developed DOFS structures and an initial study of fibrous materials adhesion to the concrete matrix. Evaluation and comparison on bending mechanical performance of DOFS reinforced concrete was performed. Furthermore it is described and presented the materials, equipments, tests and the results obtained as well as respective conclusions.

Chapter V – Conclusions and further work

Finally, in Chapter V are presented the general conclusions and the further work that should be done in the domain of the development of fibrous structures for concrete reinforcement.

References

Comprises the references used to develop the present work.

CHAPTER II

STATE-OF-THE-ART

2.1. TECHNICAL TEXTILES

Textile products are traditionally classified according to the end-uses in (Figure 2.1): Apparel, Interior and home textiles, and Industrial and Technical textiles [1]. This classification distinguishes the last two end-uses as distinct entities separate from apparel-related textiles. Each of these categories includes activities widely divergent in character [1]. According to *Euratex* (European Apparel and Textile Organization), apparel category still remains the major end-use, with 41%, followed by interior and home textiles with 33%, and industrial and technical textiles with 26% by volume of fibre usage [2].

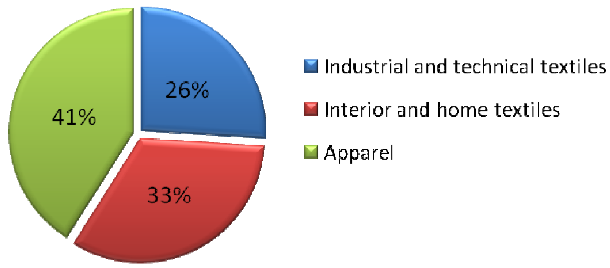


Figure 2.1 – EU textile production by 3 end-uses by volume of fibre usage-2003 [2]
(*Source*: www.euratex.org)

In the last years, technical textiles had a remarkable growth making it a desirable field. Breakthrough on production technologies and on materials science has created a whole range of technical textiles that have various applications. Thus, new fibrous materials including fibres, yarns, fabrics and other structures with added-value functionality have been successfully developed for technical and/or high performance end-uses. These innovative products with limitless range of applications cover end-uses in several areas like, civil engineering, automotive and aerospace industry, medical industry, among others. However, in apparel sector, high performance materials have aroused interest in protective wear and sports [2, 3, 4]. Figure 2.2 shows the Western Europe´s consumption of technical textile by application.

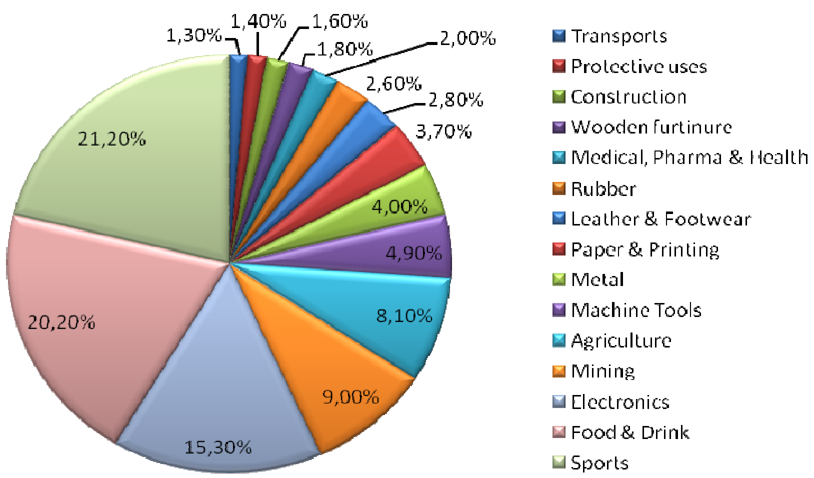


Figure 2.2 – Western Europe's consumption of technical textiles by application [2]

(*Source*: www.euratex.org)

The definition of industrial or technical textiles has been evolved during the last years reflecting the changing perceptions of the three end-uses activities [1]. For some years industrial textiles were a term used to comprise all textiles products other than intended for apparel, interior and home end-uses. According to *Horrocks* [7] this term is more widely used in the USA than in Europe or elsewhere. Once the textiles development applications were growing to areas such as, medical, hygiene, transportation, construction, sporting agriculture and many other clearly non-industrial purposes, this term was becoming inappropriate and at the moment is considered a subgroup of a wider category of technical textiles, referring to those textiles products used in the course of manufacturing operations (e.g. filters, conveyor belts, etc) or which are incorporated into other industrial products (e.g. electrical components, flexible seals etc). *Adunar* [9] defines technical textiles as specific structures designed and engineered in order to be used in products, processes, or services of mostly industrial areas. *Ridgwell* [5] *defines* technical textiles as structures which are produced mainly for their technical performance rather than aesthetic or functional properties. Thus, in general technical textiles are defined as materials and products which are designed, developed and produced mainly for their technical performance rather than their aesthetic or functional properties, i.e., materials with high technical and quality requirements such as, mechanical, electrical, thermal, durability, among others, with ability to offer technical functions [5, 6, 7]. However, the term for this type of textiles is not restricted to the words "technical" and "industrial". Terms such as, performance textiles, functional textiles, engineered textiles and high-tech textiles are also used in various contexts [7].

The most common used classification for technical textiles is given by *Techtextil*, a leading international trade exhibition for technical textiles. Due to an high product heterogeneity *TechTextil* classification provides a typology that, assembles, technical textiles in 12 groups according to end-use markets: Geotech, (geotextiles, for road construction, landscaping and civil engineering), Buildtech (building and construction), Mobiltech (automotive and aerospace industry, marine construction and railways), Sporttech (sports and leisure), Clothtech (technical components for clothing and footwear), Hometech (technical components of furniture, household textiles and floor-coverings), Indutech (filtration, conveying, cleaning and other industrial application), Medtech (medical and hygienic textiles), Agrotech (horticulture/landscape gardening, agriculture, gardening, and forestry), Oekotech (environment protection), Protech (personal and property) Packtech (packing) [8, 9, 10].

Technical textiles sector rise out, occurred in the industrialized countries like in Western Europe, North of America and Japan. For the European Union countries, this type of textiles are of paramount importance in strategic terms, once allows to achieve a world-wide leadership position. Indeed, the fact of technical textiles development and production implicates large investment in, technology, specialized staff and research, constitutes an entry barrier in this market for countries less technological developed [11].

Technical textiles is stimulating European engineering in two main areas, transportation and construction industry. According to *EURATEX*, the production of textiles for technical applications in Western Europe will grow almost 15% between 2005 and 2010, mainly due to the growing of textiles used in composites production for transportation and building and construction fields, as well as for civil engineering (reinforced plastics, concrete or metal), and due to the conventional construction materials replacement by textiles. Table 2.1 shows the research priorities in the technical textiles field sorted by market and relevance. In addition Figure 2.3 shows in the brackets the expected cumulative growth rate until 2010 of technical textiles in these markets [2].

Table 2.1 – Research priorities in technical textiles fields [2]

Technical textile application area	***Markets***	***No. of identified research priorities***
Agrotech	agriculture, aquaculture, horticulture and forestry	14
Builtech	building and construction	55
Geotech	geotextiles for landscaping, agriculture and civil engineering	20
Mobiletech	automobiles, shipping, railways and aerospace	60
Packtech	packaging	4
Indutech	filtration, conveying, cleaning and other industrial uses	24
Hometech	technical components of furniture, household textiles and floor-coverings	44

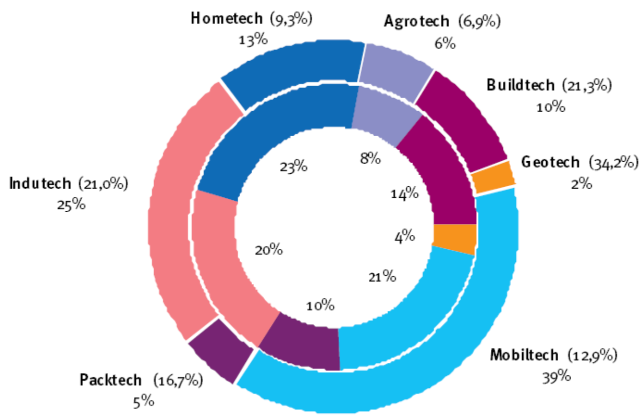


Figure 2.3 – Comparison volumes/values of Western Europe consumption of technical textiles per market in 2005 (in brackets the market segment growth rate until 2010) [2]

(*Source*: www.euratex.org)

The use of fibres, yarns or other type of fibrous structures, is the common element that ties all technical textiles applications, in order to provide a specific technical performance features so that meet the final customer or/and market requirements. Besides, they provide textile solutions for the final user needs. From technical textiles use, it is possible to obtain final products that cannot be designed with other materials or products. These products can provide better solutions than the initial materials.

The supply chain that link ups fibre producers and the end-users market is long and complex. Generally, includes big and small companies from fibre producers through yarn and fabric manufactures, finishers, converters, and manufactures who incorporate technical textiles into their own products or use them as an essential part of their business operations [7, 12].

According to *Anadur* technical textiles can be used by three basic functions [1, 9]:

1. as a component part of other product that improves directly the strength, performance and other properties of that product, e.g. composite materials reinforced with textiles;
2. as a tool to use in the production of another product, e.g. filtration textiles in food protection and paper machine clothing in paper production;
3. as a separated product which performs one or several functions, e.g. geotextiles, textiles architectural membranes, bandage fabric.

In the last years the developments occurred on fibrous materials for technical applications has been constant and intense for all over the world. One interesting and amazing fibrous material application, either being fibres, yarns, knits or fabrics is their use as reinforcement of organic, ceramic or metallic matrices leading to fibrous reinforced composite materials. In this type of material, fibres are used as reinforcement, which are responsible for the mechanical performance, while the matrix, less resistance, gives the geometrical configuration to the material and allows the loads to be transferred to the fibres. The combination of materials properties and the way they work together confers to composite materials lightness, excellent mechanical properties and excellent heat and corrosion resistance, features which allow them to be applied in a wide range of applications [20].

Technical textiles are undergoing a fast growth with forecast of 5% per year in the next 5 years [14]. This sector is responsible for one quarter of the textiles consume in terms of quantity, and, although the weak growing rates since the beginning of the decade, the forecast for technical applications it is more positive than almost other markets including fibres, textiles and garments. In terms of volume, it is foreseen a annually growth near 3,8% between 2005 and 2010. Once the tendency in using lower cost fibres and nonwovens of low cost is increasing, the growth will be slower in value terms than in terms of volume [15]. In spite of the considerable potential of technical textiles market, it should not be forgotten that it will remain a niche market. The maintenance of a broader textiles base in Europe – including all conventional products – is essential to generate the turnover and the economies of scale which are needed to remain internationally competitive [16].

Globally, some applications areas will grow faster than others. For instance, it is foreseen that geotextiles demand will increase till 5,3% annually between 2005 and 2020, being China one of the main consumers and producers. A strong growth in building and construction applications for the same period is also expected reaching equally to 5%. The research is mainly addressing to new and innovative products and for the increasing amount of textile composites in the building and construction sector. The significant growth results equally from the traditional construction materials change by textile products, in the form of non-visible components such as nonwovens, among others.

Textiles are increasing their participation on building and construction market. The textile mechanical properties produced for this end-use are often the same or higher than those of conventional materials. This type of textiles presents important features for this area such as, lightweight, resistance, strength, elasticity, corrosion resistance and degradation to chemicals and air pollutants.

In 2000, the building and construction applications consumed about 1,65 million ton of technical textiles with a value estimated of 5,9 million dollars. It is expected 2010, this volume reaches 2,6 thousand millions dollars, representing a growth rate of 57,3%, being one of the fastest rates of the 12 *Techtextil* areas.

The use of textiles in building and civil construction is intimately attached not only to the economical cycle but also to the money fluctuations available on this sector. It is expected that civil industry will grow faster than economy due to a faster population growth and to a reduction on average on the person number in the family in many western markets. Technical textiles markets will continue to benefit with the construction of big buildings and offices among others. The consumption of architectural textiles membranes is more changeable than the total textiles for construction. The civil construction applications growth will be more boosted by the increase of textiles in the sector and also by new textiles applications. The increased use of fibres in applications such as, eolian turbines and concrete reinforcement will be the source of a huge push in the fibres consumption in terms of volume [15].

Several are the applications of technical textiles in various industries such as, transportation, building and civil construction, medical and healthcare/hygiene, protection, agriculture, environment, packing, sports, military and defence, industrial processes among others [15, 17].

In civil construction, technical textiles are now competing strongly with the traditional materials such as, wood, concrete and steel. Textiles used as a single product or in composites materials, bring savings in weight, improved durability and increased performances [18]. Geotextiles are incorporated in the soil for different applications such as, reinforce, drain, protection, filtration, and separation. Another function is to ensure sealing before starting civil engineering or construction projects, roads or railways tracks, and to consolidate river banks or slopes [19]. In civil construction industry the reinforcement sector includes cables for suspending bridge platforms, curtain walling for facades, substituting concrete reinforcing steel by composite rods, concrete reinforcement with fibres, bridges repairing, and anti-corrosion conduits.

Another sector that at the moment is enjoying a strong growth is textile architecture. Architectural textile membranes are considered a technical textile. Due to several advantages which include, flexibility, lightweight, resistance to corrosion, low cost, high coverage, among others, fibrous materials are a reliable alternative to conventional roofing materials like pre-fabricated hard panels of metal or plastic. The unique properties of fibrous materials enable professionals of this area to incorporate wider, longer, and shaped structures into their designs. Polyester fabrics coated with PVC are often used in this area, making possible the construction of roofs and structures from light covers, being elegant pieces and of easy installation. From the combination of different materials and its properties and resorting to the suitable technology, new and interesting products with more than one function are being developed. One example of that interesting combination consist in the development of new architectural textiles membranes with thermal-regulating properties. The new in these membranes is the addition of PCM´s (Phase Change Materials) which are an highly thermal storage medium. New applications are also being developed for the use of textiles in interior decorating like, wall coverings, partitions, anti-noise walls, exterior or interior solar screens, shelters, conductive fibres for rooms at risk from the presence of static electricity, sealing of roofs, canopies, shielding of rooms to eliminate electro-magnetic interference, heat insulators, fire-resistance coatings and fibres for public-access buildings and semi-permeable and membranes for under-roofs [18, 22].

There are some factors responsible for the technical textiles expressive growth in the last three decades. Innovation and breakthroughs in new fibrous materials, fibres and fibrous structures processes and products, new non-textiles developments and increase of human activity, are some of those factors. However, technology innovation in fibres and fibrous structures, production processes and equipment are the most important factor in the sector. The capability of these materials to contribute for the resolution of problems in other industries is also an important factor. On the other hand, the research will continue to be an important element to solve textile and non-textiles problems, helping in the search for new and better technical textiles applications [15].

2.2. COMPOSITES MATERIALS

2.2.1. Introduction

The use of composites had its beginning in agriculture societies but it started from the industrial point of view during the second half of the 20th century as lightweight composite structures. The use of composites became very popular in spacecraft and military aircraft once they were lightweight, improved the elements performance and present high strength-to-weight ratio. Technological advances in the last decades have been allowed the reduction in raw materials as well as in processing, given us the possibility to enjoy composite materials advantages. Important applications are expected in military, aerospace and aeronautic industries. However, they will also replace in a increase way, traditional materials usually used in common engineered applications such us, in civil construction (reinforcement and rehabilitation) and in transport industry (vehicle made all of material composite) [21].

2.2.2. General characterization

In a general, it is possible do define composite material as a product composed by two or more constituents, which present distinct properties and are separated by an interface. Those elements in practice consist in [11, 23]:

- a **matrix** which provides to composite material, structure, fills the empty spaces between the reinforcement materials and allows the loads distribution;
- **reinforcement** which confers to the matrix the adequate stiffness and strength as well as other mechanical properties and also electromagnetic and chemical properties.

The final composite will possess properties not existent in the raw materials that result from the properties combination of each material, obtaining this way a single product with superior properties [11, 23, 24].

Usually a man-made composite would consist of a reinforcement phase of stiff, strong material, frequently fibrous in nature embedded in a continuous matrix phase [25]. Matrixes used can be of different nature like, polymeric (resins), cementitious (concrete), among others. Regarding to the reinforcement the most used form is the fibre, being able to resort to different types of fibrous structures. When a load is applied to a composite material the matrix, softer and more ductile, transfers the load to fibres, less ductile but much stronger. Composite materials can be divided into three main groups [20, 24]:

1. *Polymer matrix composites (PMC´s)*: are the most common composites and with more commercial interest being the fibre reinforced polymers (FRP) the most known; they use polymeric resins like thermo-set (polyester, epoxies, etc) and thermoplastics matrices (polypropylene, polyamide, etc) and a variety of e fibres such as, glass, carbon aramid, and natural fibres as reinforcement;
2. *Metal matrix composites (MMC´s)*: are easily found in transports area; these materials use metal as matrix namely aluminium and as fibres reinforcement such as carbon, glass and silicon carbide;
3. *Ceramic Matrix Composites (CMC´s)*: are used in high temperature environments; they use ceramic matrices being the most important the carbon silicides and, as reinforcement, short fibres such as glass, carbon, and ceramic, among others.

Sectors such as transportation, civil engineering, medical, among others, are only a few examples of applications fields. The main reason for the success of these materials can be found in their many potential benefits offered namely:

- low weight associated to an high stiffness and mechanical resistance that reflects directly in the component efficiency and the global structure;
- superior performance resulting from the high versatility and ability in design the material according to the requirements; composite material versatility is

obtained trough material properties optimization, geometry and production process; examples are the composites reinforced with directionally oriented fibrous structures in the most suitable directions and the production processes that allow the production of complex geometry components in a single step production;

- high potential reduction costs through, reduction on the component numbers as well as in the setting operations, reduction on initial costs and costs associated with maintenance and rehabilitation and use of some types of large scale production processes like, injection moulding or pultrusion that allow to produce composite materials at low costs and with shorter production cycles.

As mentioned by *Sousa* [11] there are several studies suggesting that, the best commitment between the resistance and tenacity should be found in the matrices with reinforcing fibres presenting high modulus of elasticity and high resistance. The new economical and environmental world state is favourable to the development of composite materials reinforced with high performance fibres that presents high modulus and resistance. Indeed, with these two characteristics it is possible to develop lightweight structures with lower global energetic content for various fields. During the last years, a substantial development has been occurred in composites for structural applications once composite materials may potentially replace traditional materials like, steel and wood. [11].

2.2.3. Classification

Several types of composite materials classification may be found in the literature. According to *Paciornik* [26] composite materials can be classified in terms of the morphology of their type of reinforcement in, particulate composites, composites reinforced with fibres and composites reinforced with structures. Figure 2.4 shows the classification given by *Paciornik*.

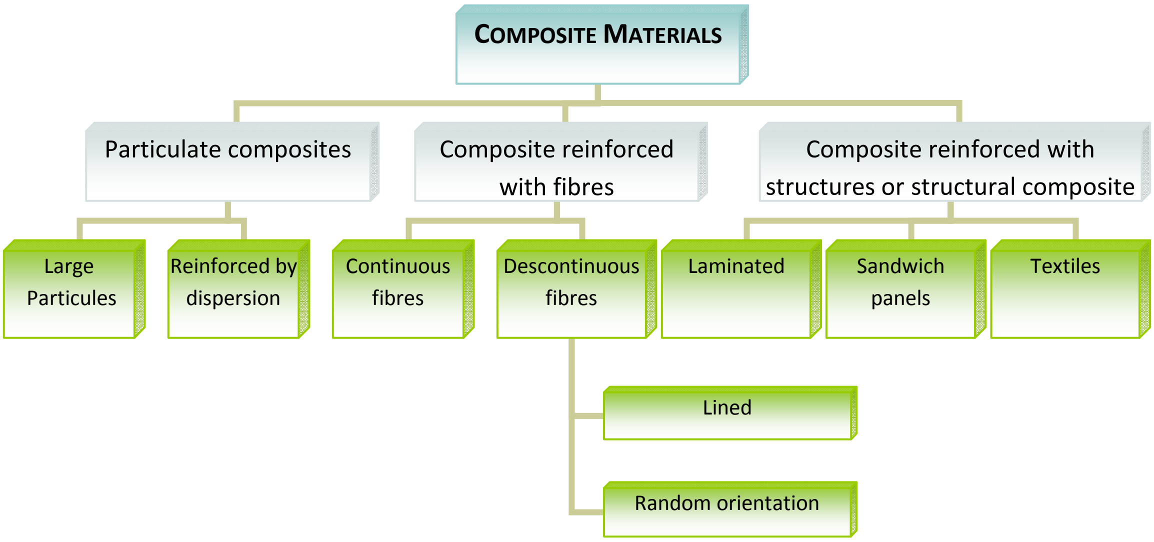


Figure 2.4 – Classification of composite materials

Particulate composite materials are composed by big particles such as, cermets (ceramic/metal), rubbers (polymer/metal) and concrete (ceramic/metal), or they could be reinforced by dispersion. In composite materials reinforced with fibrous materials, the most common fibres used are usually the glass and carbon fibre. Composites reinforced by structures are constituted by homogeneous materials and composites whose properties depend on the relative orientation of the components. Laminated materials which are composed by successive layers of an anisotropic composite with alternating orientation, sandwich panels constituted by sheets separate by one layer of less thick material and textiles or fibrous structures are examples of structural composites [26].

Another possible classification is given by *Scardino* [28] that categorize composites reinforced with fibrous materials in textiles composites, textile structural composites and textiles preform composites. Textiles composites are defined as the combination of a resin system with textile fibre, yarn or fabric system and they could be flexible or quite rigid. Tires, life rafts and heavy duty conveyor belts are examples of flexible textiles composites while fibre reinforced plastic systems used in automotive and aircraft construction is an example of the second type of textiles composites. According to *Scardino* [28] textile structural composites must have textiles as well as resin, metal, or ceramic components and must be capable of withstanding the primary and secondary loads to which the basic framework buildings, bridges, vehicles among others. Regarding to textiles preform composites, are defined as the specific assemblage of unrigidized fibrous materials. There are several types of textiles preforms presenting different fibres orientation, entanglement and geometry.

2.2.4. Composite technology

In composites reinforced with fibres, the fibrous material present variable length, orientation and volume content. In some cases, it is necessary pre-impregnate the reinforcement in order to obtain a better adhesion between fibre and matrix. The final result is a heterogeneous composite material highly isotropic (properties are constant independently of the direction) [26].

The most common used fibrous materials in composite reinforcements are glass, carbon/graphite, boron and aramid fibres as well as metallic and ceramic fibres. The reinforcement provided by the fibres can be classified in [11]:

- unidirectional: composed by fibres which are oriented according to one space direction;
- two-dimensional: composed by planar structures like woven, nonwoven, knit and braid;
- tridimensional: composed by preform structures or with directionally oriented fibres according to several space directions.

Regarding to the composite matrices, the raw materials commonly used are, organic (thermo-set and thermo-plastic), mineral, metallic and ceramic. Matrices are organic elements of high molecular weight being the result of polymerization addition reactions or the condensation of several basic components. The main matrices used in the composite productions are: [20].

- *thermo-plastic*s: polypropylene (PPS), polyamides (PA), polycarbonate (PC), saturated polyester (PET-PBT), poly-acetal (POM), polysulphidephenyl, polyetheretherketone (PEEK) etc;
- *thermo-set*: unsaturable polyesters (UP), polyepoxys (EP), polyamides (PI) etc;
- *elastomeric*: polyurethanes (PU) and silicones (Si).

Nevertheless, there are other types of matrices usually used in specific fields like in civil construction. In this area cementitious matrix is commonly used being responsible either for the composite stiffness.

The fibrous materials used in composites can be applied in different forms. The most common are crushed fibres, chopped fibres of continuous filament, texturized yarns, rovings of continuous filaments, mats and fabrics [27]. However, they can also be found under other structures, more and more used, such as warp and weft knits, braids and hybrids (combination of different fibrous structures, like for example, nonwovens with fabrics).

According to *Araújo* [11, 20] there are four important levels considered in the mechanical study of composite reinforced by fibrous materials:

Fibre→ Yarn → Fabric →Composite

However, this sequence can be changed, once for some composite production it is possible to use fibres directly into the composite like, for example, in filament winding. In this case the sequence is:

Fibre → Yarn → Fabric → Composite

With the appearance of nonwoven structure, the yarn production costs were avoided and the sequence changed to:

Fibre → Fabric → Composite

Finally, with some production methods such as, moulding by injection moulding of disperse fibres in resin, the sequence is reduce to:

Fibre → Composite

One of the main reasons to use fibrous materials in composites is their mechanical behaviour namely to the tensile strength.

Traditionally composites reinforced with fibrous materials have been reinforced plastics with chopped fibres and continuous filament.

Wovens, in the recent years, have been used in laminates becoming an important reinforcement structure mainly, as they allow an higher variety of complex shapes and an higher performance when compared to the chopped fibres or continuous filaments. Besides, they also allow the possibility of significantly reduce labour costs, eliminate operations, and the combination with the structure in the incorporated elements formation for the composite materials reinforcement.

Using the hybrid fabrics it is possible to obtain economy, reliability and versatility in the composite production. The most important economic advantage is regarding to the reduction costs on the yarns used for accomplish the requirements of specification and performance [20, 27, 28].

2.2.5. Composite interface

In composites, the interface, adhesion and the reinforcement mechanism are parameters extremely important. Thus, they need to be considered once they influence the composite mechanical properties namely, tensile and impact strength, and therefore their performance. Interface is referred to the link considered from zero thickness between the fibre and the matrix. Once the matrix receives fibrous reinforcement, an intimate contact occurs and adhesion could happen. This adhesion can be mechanical, chemical, electrostatic, or by inter-diffusion. Interface besides being responsible for the loads transmissions from the matrix to the reinforcement agents also, allow the molecules penetration such as water. There are several interfacial treatments being able to change the interfacial composite properties. However, none is able to prepare specific structural interfaces, leading to the production of uncontrolled and unchangeable interfaces. On the other hand, progresses in interface field are going on and intelligent interfaces are under research with structures specifically designed and built in order to carry out multiple tasks. In composites for structural ends the development goes towards to interfaces not only capable of transmit loads but also capable of adding energy dissipation mechanisms during the crack propagations performance [11].

2.2.6. Composite advantages

As mentioned before composites present a wide range of applications in various areas, due to their unique and excellent properties, such as [11, 13]:

- high specific stiffness and strength;
- high corrosion, fatigue, flame, impact and crash resistance;
- thermal stability and low conductibility;
- reduction on the component number;
- anisotropic behaviour and inert to chemicals;
- do not plasticize, their plastic limit corresponds to the rupture, feature important to composites subjects to tension concentrations.

Composite materials reinforced by fibrous materials support cycle loadings without presenting fatigue. High resistance to corrosion is other typical feature enabling their use in marine and chemical environments. The high specific stiffness and strength are still the combination that places composites in new applications areas. Nevertheless, the high capacity of absorption and the low thermal expansion coefficient are properties can be optimized for specific applications. Advanced composites besides reducing problems related to fatigue, allow an higher conception and production flexibility which can lead to a reduction on the number of components to be produced. However, the main advantage of composite materials is the fact that they could have the required specific properties. Resistance to high extreme temperatures, corrosion and wear are benefits obtained when using composites in to industrial applications.

The mentioned composite advantages can lead to lower costs and to product life cycle reduction. This fact combined with the reduction on raw materials costs as well as in their production, due to technological advances, will allow to benefit from their multiple advantages.

2.3. FIBROUS MATERIALS FOR COMPOSITE REINFORCEMENT

2.3.1. Introduction

In composites reinforced by fibrous structures for structural applications, the amount (fibre volume fraction) and the orientation of the fibre in the composite, the fibre geometry, and the basic mechanical properties of the fibre are extremely important, once they determine composite characteristics and respective performance. This involves the right selection of the fibre material and consequently the right production techniques, considering product performance, productivity and costs [20, 24].

To obtain an effective reinforcement, fibres with high mechanical properties, such as tenacity, breaking elongation and modulus of elasticity should be used. These properties should be much higher than the concrete matrix otherwise the stiffness will decrease the building component when cracks occur. Besides, fibres should withstand alkaline environment without losing their properties to ensure the service life of concrete. The process of manufacturing determines largely the amount of fibres in the composite. The geometry of the reinforcing fibres are also an important property as they are designed to loaded in their length and not across their width, i.e., their highest mechanical properties are along their length. Thus, the fibre orientation creates highly specific direction properties in the composite which leads to the highly anisotropic properties of the composites. Anisotropy could be a good advantage in composite design, once the greater part of the fibres are going to be placed along the orientation on the main load paths, avoiding this manner that loads will be applied in unnecessary material. Fibres could be placed with a specific orientation or randomly. The variation in strength and stiffness of fibres could be seen as an advantage, because it is possible to develop a material with the required strength or stiffness in the direction in which these properties are required.

Other fibres important requirements are, processability, small relation when under permanent load, good and constant adhesion between the fibre reinforcement and concrete and the low cost [24, 29].

Fibres could be used as chopped fibres, filaments, rovings or yarns through different textile production processes usually used for conventional textiles such as, weaving, knitting, braiding and nonwovens production techniques. Their selection depends strongly on the cost expected of the material, performance and composite production technique. From the point of view of mechanical performance, textile production techniques can produce interesting fibrous structures such as, tridimensional or directionally oriented structures. [20]. Table 2.2 presents basic mechanical properties of some high-performance fibres as well as other engineering materials.

Table 2.2– Basic mechanical properties of fibres and other engineering materials [24]

Material Type Grade	**Tensile Strength (MPa)**	**Young´s Modulus (GPa)**	**Typical Density**	**Specific modulus (GPa)**
Carbon HS	3500	160 – 270	18	90 – 150
Carbon IM	5300	270 – 325	18	150 – 180
Carbon HM	3500	325 – 440	18	180 – 240
Carbon HUM	2000	> 440	20	> 200
Aramid LM	3600	60	145	40
Aramid HM	3100	120	145	80
Aramid UHM	3400	180	147	120
Glass – E glass	2400	69	25	27
Glass – S_2 glass	3450	86	25	34
Glass – quartz	3700	69	22	31
Aluminium (5083)	130/280	72	2.8	26
Titanium (125)	250/400	105	4.5	23
Mild Steel (43A)	275/460	205	7.8	26
Stainless (316)	206/520	196	7.9	25

Fibres like polypropylene, polyvinyl alcohol, polyethylene and polyacrynitrile, basalt fibres, and fabrics made of metal yarns could also be used as fibre reinforcement [29].

As mentioned by *Sousa* [11] the criteria to select the most appropriate raw material include:

- mechanical properties of the product depends directly on the reinforcement percentage and fibres orientation; it is possible to have three different situations:

    1. all fibres are oriented in the same direction; final product presents higher resistance;
    2. the reinforcement includes perpendicular orientations, in this case the resistance will be high but not so high as the previously situation;
    3. there is no specific orientation of the fibres; the final product will present a lower resistance;

- the selection of the fibre material determinates the production process;
- it is necessary a good study on the raw material and consequently on the manufacture techniques to obtain an optimal relation between the cost and quality.

2.3.2. Fibres and filaments

Nowadays there are a several types of high-performance fibres commercially available. These fibres range could be from polymeric such as, aramid and extended-chain polyethylene to carbon fibre, boron fibre, ceramic fibres like silicon carbide and alumina, and metal fibres such as steel. All these fibres have some features in common, as they are stronger and rigid/stiffener than traditional metals fibres like steel and aluminium. However, they present more advantages depending on the final product application.

At the moment there are current and potential applications for fibre reinforcement composites but they cannot be called "structural" due to function played which is mainly to exploit other physical properties rather than only mechanical strength [38].

Regarding to the fibre costs (Figure 2.5.), fibres used in lightweight fabrics which are of small bundle size (linear density - tex) are considerably more expensive, than the heavier bundles of fibre, which normally are used in unidirectional fabrics [24].

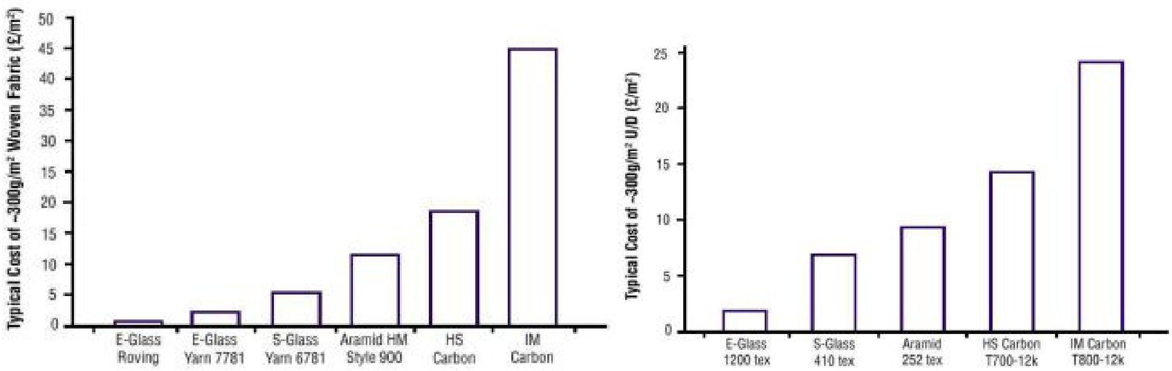


Figure 2.5 – Fibres costs comparison of an typical price of a 300 g/m^2 woven fabric [24]

(*Source*: www.netcomposite.com)

Usually high-performance fibres, such as glass, carbon and aramid can be made up in the form of filament or yarn. However, filaments are the better option for reinforcement due to their low structural elongation [29].

The main fibres used in composite materials namely of cementitious matrix are: glass fibre, aramid fibres, carbon fibres, several synthetic fibres (polypropylene, etc), fibres, metal fibres (steel fibres) and natural fibres.

2.3.2.1. Glass fibres

Nowadays, glass fibre is well accepted in the production of high performance composite materials [39]. The composition of these fibres is a blend of silicates and usually is composed by silica sand, sodium carbonate, aluminium hydroxide, limestone and borax. The production process is based in the fusion of different materials about 1300^o C followed by extrusion and drafting processes. Fibre glass has been the material more used in production of several textile composites due to its versatility, consistence and reliability.

Glass fibre has excellent dielectric properties, namely sound insulation and thermal resistance. They also have good tensile and tearing resistance, high modulus, dimensional stability and interesting relation features/cost [11, 20, 40].

Varying glass composition it is possible to produce different types of glass fibres. The right selection of glass fibres for a specific application depends on economical and application issues. Glass fibres used in structural reinforcements are [24, 29, 39, 41]:

1. *A-glass fibre*: usually used as insulating material in thermal and acoustic applications;
2. *E-glass fibre*: lower alkali content and stronger; good tensile and compressive strength and stiffness; good electrical properties and relatively low cost; poor impact resistance; is the most common of reinforcing fibre used in polymer matrix composites; the main application is the automotive industry because of great weight savings; it is also often used in textile field and composite production were it is used as reinforcement in 90 % of the cases; this fibres is available in strand, yarns and rovings;
3. *C-glass*: presents the best resistance to chemical attack; mainly used in the form of surface tissue in the outer layer of laminates;
4. *R-glass*: higher tensile strength and modulus than E-glass fibre and also with better wet strength retention; is used in special applications namely, space program and defence due to their performance relatively to the fatigue, moisture and temperature;
5. *S-glass*: characterized by an high stiffness is often used in applications where good mechanical properties are required;
6. *AR-glass*: used in concrete reinforcement once they contain more than 15% (mass) of zircon which confers to the fibres an excellent alkali resistance; high tensile strength so, when it is used as concrete reinforcement which has high

compressive strength the composite effects results in a strong material; glass fibres improves concrete modulus and durability, so they are used for durable structures.

Glass fibre is used to produce glass reinforced cement (GRC) which has a wide range of applications namely, in architectural cladding components and facades plates [65, 66].

2.3.2.2. Carbon fibres

Carbon fibres have being conquered some sectors in the composite market. This fact could be explained by the need of using fibres with good relation between the stiffness/weight and modulus/weight [20].

Carbon fibres are obtained, in general, through a precursor fibre, being the most common polyacrylonitrile (Pan) but could be also produced from cellulose or pitch [20, 24, 42]. The most generally recognized carbon fibres classification is related to the modulus range being grouped as follows [24, 39]:

- High Strength – HS;
- Intermediate Modulus – IH;
- High Modulus – H;
- Ultra High Modulus - UH.

Most of these fibres have more or less the same diameter (5 – 7 µm) and it is possible to find them in different shapes, such as rovings (500 – 10000 filaments) fabrics (unidirectional and multidirectional), hybrid fabrics and epoxy pre-impregnated. Normally carbon fibres are produced and sold in rovings. Carbon fibre properties can be summarized in [20, 24, 39, 42]:

- has the highest specific stiffness of any commercially available fibre;
- very high mechanical resistance, either in tensile and compression;

- high resistance to corrosion, creep and fatigue;
- non – inflammable;
- inert;
- impact strength lower than glass or aramid;
- electric conductive;
- brittle.

Continuous rovings are normally pre-placed and aligned to provide the optimum fibre orientation during fabrication. Chopped fibres are generally incorporated during the mixing process and are therefore orientated randomly throughout the mix. A satisfactory mix of chopped carbon fibre, cement and water is difficult to achieve because of the large surface area of the fibre. Carbon fibres have a wide range of choice which is suited to different applications. This type of fibres allows not only the reduction of weight but also resistance to corrosion, spalling and freeze-thaw cycling [41].

2.3.2.3. Aramid fibres

Aramid fibres are a man-made organic polymer (an aromatic polyamide) produced by spinning a solid fibre from a liquid chemical blend. They are characterized by excellent tensile strength due to low density that gives a very high specific strength, high modulus of elasticity, good abrasion resistance, and chemical and thermal degradation. However, they can degrade slowly when exposed to ultraviolet light.

Aramids could be from two different types, meta-aramid and para-aramid, presenting each one different properties. Para-aramid provides superior mechanical stability which is very interesting for reinforcing purposes.

Comparing to previous fibres, aramid presents lower density, lower brittleness and higher impact resistance. Aramid has two disadvantages that confine their use in composites: if the heat expansion in reinforcement material and concrete are different there will be problems related to the adhesion of both components; they present low alkali resistance [24, 29].

The cost depends of the filament count and usually they are available in the form of rovings or fabrics [20, 24].

2.3.2.4. Other fibres

There are other types of fibres which can be used in advanced composite structures for civil applications although they are not often used.

2.3.2.4.1. Polyester

It is an organic fibre obtained from the poly-condensation reaction between the terephthalate acid and ethyleneglycol. Thermoplastic fibre characterized by a low density, high tenacity, good impact resistance and low modulus. However, it is relatively hydrophobic. Normally are used when low weight, high impact or abrasion resistance and low cost are required. Polyester fibres have been used at low contents (0,1% by volume) in order to control plastic-shrinkage cracking in concrete [11, 24, 65].

2.3.2.4.2. Polyethylene

Polyethylene has been produced for concrete in monofilament form. Concrete reinforced with polyethylene fibres at contents between 2 and 4% by volume exhibits linear flexural load deflection behaviour up to first crack, followed by an apparent transfer of load to the fibres permitting an increase in load until the fibres break [65].

2.3.2.4.3. Polypropylene

Polypropylene fibre is a synthetic hydrocarbon polymer that was firstly used to reinforce concrete in the 1960´s. Polypropylene fibres are produced as continuous mono-filaments, with circular cross section that can be chopped to required lengths, or fibrillated films or tapes of rectangular cross section. Polypropylene fibres are hydrophobic and therefore have the disadvantages of poor bond characteristics with cement matrix. This fibre presents a low melting point, high combustibility and a relatively low modulus of elasticity. Although, this fibres are tough they have low tensile strength and modulus of elasticity as well as a plastic stress-strain characteristic. Polypropylene monofilament has inherent weak bond with the cement matrix fact, which could be explained by their relatively small specific surface area. However, this problem could be enhanced resorting to fibrillated polypropylene fibres that provide larger specific surface area. Polypropylene fibre contents of up to 12% by volume are claimed to have been used successfully with hand-packing fabrication techniques, but volumes of 0,1% of 50mm fibre in concrete have been reported to have caused a slump loss of 75 mm. Polypropylene fibres have been reported to reduce unrestrained plastic and drying shrinkage of concrete at fibre contents of 0,1 to 0,3% by volume [65].

2.3.2.4.4. Metallic fibres

Metallic fibres are obtained by different techniques, such as, lamination, liquid projection and wiredrawing. High density and a high cost are drawbacks of metallic fibres [20]. Metallic fibre mostly used in concrete reinforcement is steel fibres. They present an high tensile strength (0,5 – 2 GPa) and modulus of elasticity (200 GPa), a ductile/plastic stress strain characteristic and low creep. The lack of corrosion resistance of normal steel fibres could be a disadvantage in exposed concrete situations where spalling and surface staining are likely to occur [65].

2.3.2.4.5. Natural fibres

Natural fibres can also be used but in other perspective. It is possible to use fibrous materials, such as jute, flax, and sisal as composite reinforcement namely in cementitious matrices, although, in low tech applications knowing that fairly high strengths can be achieve. Natural reinforcing materials can be obtained at low cost and low levels of energy which is an advantage. Use of natural fibres as concrete reinforcement is of particular interest to less developed regions where conventional construction materials are not readily available or are too expensive [24, 65, 66].

2.3.2.5. Mechanical properties and cost comparison of fibres

Table 2.3 shows a basic comparison of main desirable characteristics of different types of fibres.

Table 2.3 - Comparison properties of advanced reinforcing fibres [24]

Property	Aramid	Carbon	Glass
High tensile strength	**	***	**
High tensile modulus	**	***	*
High compressive strength	*	***	**
High compressive modulus	**	***	*
High flexural strength	*	***	**
High flexural modulus	**	***	*
High impact strength	***	*	**
High interlaminar shear strength	**	***	***
High in – plain shear strength	**	***	***
Low density	***	**	*
High fatigue resistance	**	***	*
High fire resistance	***	*	***
High thermal resistance	***	*	**
High electrical insulation	**	*	***
Low thermal expansion	***	***	***
Low cost	*	*	***

***Excellent; ** Medium; * Poor

Figure 2.6 illustrates a comparison on tensile behaviour of few high-performance fibres used in composites, namely in cementitious matrix and metals [11].

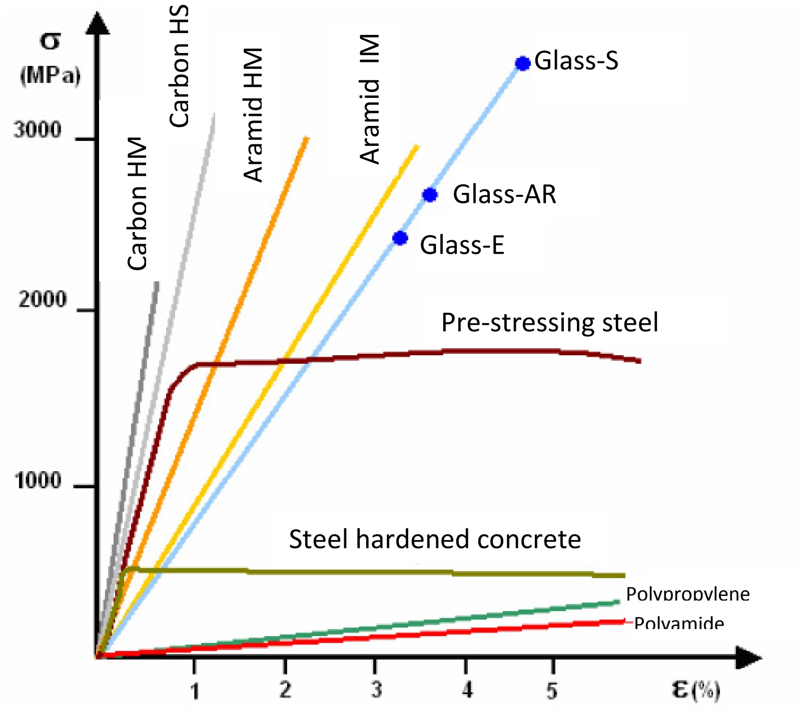


Figure 2.6 – Tensile behaviour comparison of some high-performance fibres [11]

2.3.3. Yarns

According to *Scardino* [28] a yarn is a linear assemblage of fibre formed into a continuous strand having textile-like characteristics like for instance, substantial strength and flexibility. Usually they are not used alone in composite reinforcement instead their use in this domain is to enable the production of oriented structures in several directions through different textiles processes. For this application their aim is to be the intermediary between fibre properties and the fibrous structure like in wovens, knits and braids.

The yarn properties depend directly on the physical properties of the filaments and the yarn structure. The majority of the high modulus fibres can be modified to produce yarns with different structural configurations. Yarn structural features (fibre packing, density, fibre segment length and mobility of fibre segment) are dependent on fibre geometric properties (fibre length, fineness and crimp) and also by the yarn processing system features (fibre orientation and entanglement). Figure 2.7 shows the friction on the glass fibres during stitch-bonding process.

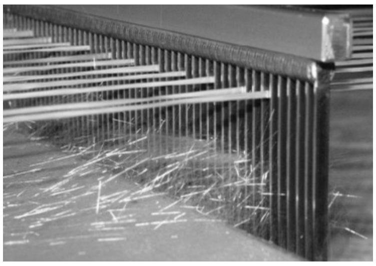


Figure 2.7 – Glass fibres friction during stitch-bonding process [44]

In high modulus materials, the transference capacity is much lower due to fibre degradation during their production. This type of fibres do not perform well in surface, compressive or bending stresses so it is usual that they only present 50% of their strength or modulus in the fabric. In order to overcome this problem, it should be used equipments, finishing's, and other special precautions to accomplish higher fibre-to-yarn and fibre-to-fabric.

It is possible to use man-made fibre yarns combinations obtaining hybrid yarns. These yarns have a hybrid structure and are made of different types of fibres. Hybrid yarns are obtained by friction spinning or by co-extruding process and can be used in concrete reinforcement. An example of the first type of yarn is an hybrid yarn made of AR-glass or carbon filaments as core and AR-thermoplastics as a mantle and for the second type a core yarn is spray-coated with another polymer [20, 28, 29].

2.3.4. Fibrous structures

2.3.4.1. Introduction

The use of fibrous structures as reinforcement of cementitious composites is potentially quite attractive. Fibrous structures namely knitted, woven and braided have been recognized as a very attractive composite reinforcement material due to the possibility of producing preforms, allowing fibre orientation according to the application needs, conformability and handling [36].

Regarding to the production process, there are only few which can be used to manufacture fibrous structures for concrete reinforcement. Each manufacture process allows the production of a wide range of composite reinforcements with the required mechanical properties. The most important factor in these structures is the possibility to create an open structure, like a grid, with high stability not only, to get a good permeability/adhesion with concrete, but also to ensure a reasonable handling of the structure once the yarns/filaments cannot displace [28, 29]. The main textile technologies to produce fibrous structures for composites are weaving, knitting, braiding and nonwovens production techniques [11].

For each one it is possible to produce from conventional to innovative structures. The selection of the appropriate structure depends on the financial nature and also on the main restrictions imposed by the application itself.

2.3.4.2. 2D fibrous structures - planar or conventional structures

According to *Gries* [50] a textile is defined as two-dimensional if it does not extend in more than two directions, neither in yarn architecture nor in textile architecture. Wovens, knitted, braided and nonwovens fabrics are examples of this type of structure.

The properties of fabrics depend on the characteristics of the constituent yarns or fibres and on the geometry of the formed structure.

2.3.4.2.1. Woven structures

Conventional woven fabrics are produced by interlacing two sets of yarns: one called warp whose yarns are along the length of the fabric, while the other is weft whose threads run along the width of the fabric. Both set of yarns are mutually positioned under the angle of 90º (warp ate 0^0 and weft at 90^0). The warp and weft yarns can be interlaced in diverse ways having like this a regular pattern called the weave structure. Afterwards a brief description of the most common weave structure is made [24, 28, 39]:

a) *Plain weave* (Figure 2.8a): is the simplest woven structure and it is characterized by each warp fibre passes over and under alternately of each weft fibre. This structure is symmetrical, with good stability and reasonable porosity. However, presents several disadvantages such as, difficulty to drape, and high level fibre crimp that leads to low mechanical properties.

b) *Twill* weave (Figure 2.8b): structure made up of one or more warp fibres alternately weave under and over two or more weft fibres in a regular and repeated manner which produces diagonal lines on the face of the fabric. They possess superior wet out and drape rather than plain weave but with less stability.

c) *Satin weave* (Figure 2.8c): is characterized by fewer interactions between warp and weft, with binding places arranged to produce a smooth fabric surface without twill lines. This weave structure is asymmetric, very flat, has good wet out, high drape, low stability and low crimp which confers good mechanical properties.

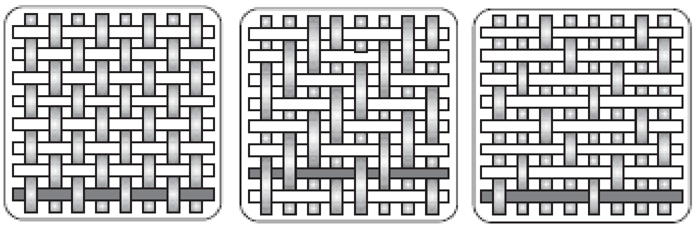

(a) (b) (c)

Figure 2.8 – (a) Plain weave (b) Twill weave and (c) Satin weave [24]

Table 2.4 presents a comparison regarding to the structure properties above mentioned.

Table 2.4 – Comparison of some structures properties

Properties	***Plain***	***Twill***	***Satin***
Good stability	****	***	**
Low porosity	***	****	*****
Symmetry	*****	***	*
Low crimp	**	***	*****

*****Excellent; ****Good; ***Acceptable; **Poor; *Poor

Woven fabrics are usually dimensionally stable although possess lower extensibility and porosity rather than other structures. The mechanical properties of woven fabrics are very important for composites and they depend on different factors, namely raw materials, warp and weft count, yarn density and weave structure. According to *Demboski* [39] the strength of fabric is higher in warp and weft direction while in diagonal direction they present lower mechanical properties, higher elasticity and lower shear resistance.

Some disadvantages related to the fabrics which can difficult some composite designs are, their tendency to unravel at edges when it is cut, anisotropy, limited conformability, reduction on traction efforts transference from the yarn to the fabric due to crimp and difficult handling of open structures. Notwithstanding, some of these inconvenient can be overcome resorting to special fibrous structures like for instance triaxial wovens. This type of structures are produced by the interlacing of three yarn systems at 60^{o} angles providing this way an enhanced isotropy, higher in-plane rigidity, more uniform conformability and less problems in the handling of very open structures. Nevertheless none of woven fabric structure offers sufficient extensibility [20, 28].

Woven fabrics usually used in concrete reinforcement are composed by rovings or yarn continuous filaments with the same linear mass or different in the warp and weft [20]. The reinforcement can be made with flat woven and multi-layer wovens. The first ones are usually used to stop crack propagation in plaster mortar but they can also be used in reinforcement foam, gypsum and wood elements, acoustic and heat insulation sandwich structures. A requirement for the reinforcement of concrete is to have an open structure with threads in the cross direction very stabilized even if for that it is necessary to use an anti - displacement finish. The multi-layers are several layers that are attached by a binding warp thread, resulting in defined space between the layers [29].

According to *Peled et al* [43] rovings from wovens improves bonding performance by providing mechanical anchoring to compensate the poor interaction between hydrophobic reinforcing fibres. Refers also studies made that confirming composite reinforced with woven structure presents an increased flexural strength and toughness even if the woven is made with low modulus hydrophobic fibres. However, these studies did not deal with fabric bond characteristics. A few years later, *Peled* and *Bentur* [45] have realized a study regarding to the fabric structure efficiency in textile reinforced cement composites and concluded that, in cement composites the woven fabric geometry may have a marked effect on the composites properties. Enhanced bonding of a fabric structure was found to occur when a non-linear geometry is induced in individual yarns by the fabric structure and the woven transversal yarns influence cement composite. According to them at one extreme, fabric geometry, may enhance bonding resulting in a strain hardening behaviour of low modulus yarn composites, at the other extreme it may reduce drastically the efficiency of a high performance bundled yarn that is very effective for reinforcement when it is not part of a fabric. Besides, the perpendicular yarns treated as “non-structural” with the objective of providing a mechanism to hold the longitudinal yarns in place during the production of the composite may have significant and opposing influences in the cement composite: in woven fabric structures they enhance bonding and therefore an increase in their density (up to an optimum value) is beneficial.

2.3.4.2.2. Knitted structures

Knits are fibrous structures characterized by a basic structure called loops and are produced by the interlooping of one or more yarns. Those yarns if possess an high modulus allows the production of a wide range gamma of knits with different behaviour and shapes.

Two different basic textiles technologies allow the manufacturing of knitted structures: weft and warp knitted technologies. Both types of knits produced by these technologies can have an determinate extensibility in a specific direction and through yarns, which do not knit, is possible to project knits with a stability in one direction and with deformability in the others directions [20, 28, 39].

The biggest disadvantages of these structures for specific applications are their thickness and high consume of yarn in relation to the covering degree. A potential limitation of knitted fabrics is their high porosity, which unlike woven fabrics cannot be reduced below a certain value determined by the construction. As a result, applications requiring very low porosity usually incorporate woven materials [11, 28]. Another drawback which is associated to this type of fibrous structure is regarding to the use of brittle fibres, such as glass and carbon fibres. Once this type of fibrous materials are extremely brittle, the process formation of loop and the loop structure itself can serious damage the fibres leading to a worst performance of them. The major advantage of knitted materials is their flexibility and inherent ability to resist unravelling when cut.

Warp knitted fabric

All loops of the warp knitted fabric are formed from a separate yarn called warp mainly introduced in longitudinal fabric direction. In this structure neighbouring loops of one course are not being created from the same yarn (Figure 2.9). These structures have mechanical properties very similar to those of woven fabrics, however, are very flexible and, depending of the construction, they can be elastic or inelastic.

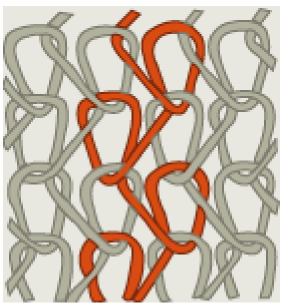


Figure 2.9 – Warp knitted structure [46]

(*Source*: http://www.bbc.co.uk/schools/gcsebitesize/design/textiles/fabricsrev_print.shtml)

Some special warp knits structures named weft inserted warp knits can be produced with maximum stability resorting to lain-in yarn systems in biaxial directions. Usually are used to manufacturing composites being of huge interest as this structure preserves the yarns properties and due to this flexibility in design performance requirements from complete dimensional stability to directional elongation. Besides, they provide higher yarn-to-fabric tensile translation efficiencies, greater in-plane shear resistance and better handling in open structures when compared to wovens. Thus, for composites it is possible to use weft inserted warp (Figure 2.10a) knit characterized by an insertion of yarns in weft direction and multibar weft inserted warp knit (Figure 2.10b) where at the same time yarns are inserted in warp and weft direction. The reinforcing yarns are introduced in the structure without crimp allowing the optimization of mechanical properties. Moreover they offer the possibility of greater woven fabric width and greater productivity [20, 28, 39].

Figure 2.10 – (a) Weft inserted warp knit (b) Multibar weft inserted warp knit [39]

The equipment used for the production of warp knits are the Tricot and Raschel looms. The first equipment does not produce complex structures, is finer in gauge and is more rapidly, while the second produces more complex structures but it is slower in speed production [47].

Weft-knitted fabric

Weft-knitted fabric has loops in one row of fabric formed from the same yarn. The horizontal row of loops in a knit is called a course and the one that is in vertical row is called wale (Figure. 2.11).

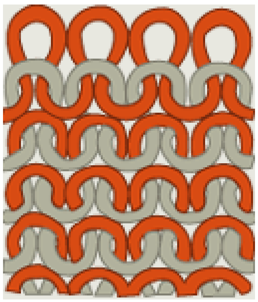
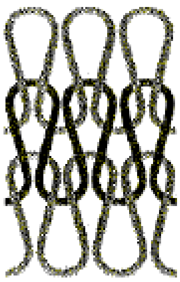


Figure 2.11 – Weft-knitted structure [46]

(*Source*: http://www.bbc.co.uk/schools/gcsebitesize/design/textiles/fabricsrev_print.shtml)

One important factor that influences the properties of weft-knitted is the stitch length - length of a yarn in a knitted loop. The simplest weft knitted structure is named jersey (Figure 2.12a) and it is produced by needles which are in one needle bed machine. But, if it is used needles from both needles bed the structure produced is called rib (Figure 2.12b).



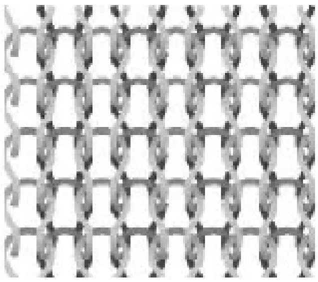
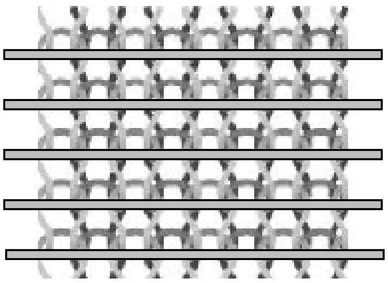


Figure 2.12 – (a) Jersey structure (b) Rib structure [39]

These structures may be produced using circular or flat knitting machines. The first type can be classified in three classes: the single jersey equipment which has one set of needles and only makes jersey, the dial and cylinder equipments which have two sets of needles and makes jersey and rib knits and the double cylinder purl equipment which uses double ended latch needles and manufactures purl structures. So, different types of structures can be produced [47].

Weft-knitted fabrics have been seen their application limited in composite reinforcement namely due to their poor mechanical properties. The main reason for that is due to tensile behaviour of weft-knitted fabrics which is strongly restricted by loop formation. During the application of a tensile load, the loops change their shape in order to accommodate the applied load. In this part of deformation small loads lead to large displacement leading to a typical behaviour of a low stiffness material. Nevertheless due that behaviour knitted fabrics are particularly suitable for applications where resistance to impact and absorption of energy are the main requirements [67].

Weft-knitted structures are elastic, stretchable and easily deformed. However, to be used in concrete reinforcement these structures present a disadvantage, stress is transmitted for only short lengths along the fibres before being interrupted by the weaker matrix. Although this drawback, exists the possibility of overcoming this problem through orientated yarns introduction in the weft-knitted structure. Thus, a new structure is produced with higher mechanical properties that can be used in composite application. Figure 2.13 presents some examples of those new structures: Figure 2.13a shows a weft knitted fabric (uniaxial) and in Figure 2.13b is a biaxial plain weft knitted structure [39].



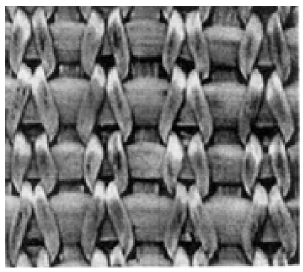


Figure 2.13 – (a) weft knitted fabric with inserted yarns in course direction [39] (b) biaxial plain weft knitted structure with inserted yarns in course/wale direction [39]

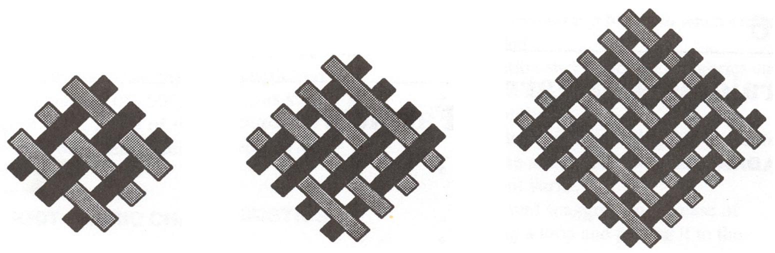
Comparing weft and warp knitted structures with woven structures it is possible to conclude that:

- weft knitted fabrics are very extensible and dimensionally unstable unless additional yarns are used to interlock the loops and reduce the extension while increasing elastic recovery and they have inferior mechanical properties especially regarding to composite applications.

- Warp knitted structure is extremely versatile, and can be engineered with a variety of mechanical properties similar to those of woven fabrics [39].

2.3.4.2.3. Braided structures

Braided textile structures are produced by interlacing different yarn systems in a tubular form. There are three main types of braided structures: diamond (Figure 2.14a), regular (Figure 2.14b) and hercules (Figure 2.14c).



(a) (b) (c)

Figure 2.14 – Braid structures (a) diamond (b) regular (c) hercules [39]

Diamond structure is obtained when yarns cross alternatively over and under the yarns of opposite direction and in this case the rotation is one to one. This rotation may be modified to, two by two and three by three to obtain the others two structures [39]. From these structures the diamond is the most stable and hercules is the one that presents the lower stability [48].

As mentioned by *Demboski* and *Bogoeva* [39] braids are produced in a tubular form of biaxial yarns, however, if it is inserted yarns (middle-end-yarn) oriented longitudinally into the structure a three axial braid is obtained (Figure 2.15a). Also it is possible to insert in the middle of the tubular form fibre bundles obtaining like this a triaxial structure with axial fibres (Figure 2.15b).

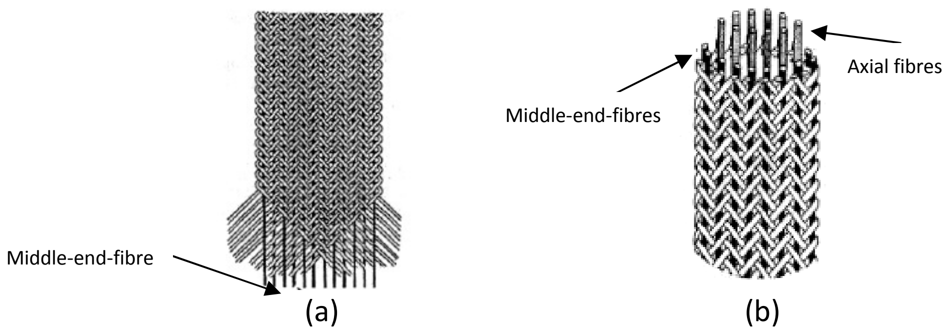


Figure 2.15 – Triaxial braid structures [39]

Braided diameter is controlled by some parameters namely, number of fibres, intertwining yarns angle, number of fibre intersections per unit length of the yarns and fibre linear density (tex) [24]. The intertwining angle can vary between 10-80^0 and it is the main feature of a braided structure being influenced by few factors, such as, yarn fineness, type of the structure (biaxial or triaxial), cover factor and longitudinal yarns volume ratio [39].

Depending on the yarns orientation and on their number per transversal section (thickness direction), braids can be classified in to 2D or 3D. The first technology has been used specially in the production of hollow pieces with or without core and for coatings (electrical cables) and they consist in two or three yarn diameters oriented, that cross in *xy*. 2D braids can be planar or circular. 3D braids present three or more yarn diameters per transversal section in thickness direction and. Their applications are very specific solving situations where the relation between weight and strength are extremely important [48]. The 3D braiding technology is a very suitable technology to manufacture complex textile preforms [49].

Braid is a flexible product and can be manufacture in various shapes, using a mandrel which can shape the braid in several forms during the manufacturing stage. Their limitations are related to the equipment presenting restricted width, diameter, thickness and shape selection. Braid structures have weak axial stability and compression in yarns direction and are conceived to have multidirectional conformability [20]. Regarding to 3D braids their major limitation are productivity and fabric length [28, 39].

Nowadays braids are the reinforcements which have more applications variety on the market.

2.3.4.2.4. Nonwovens structures

Defining nonwovens is not a very easy task due to the wide range of products which are available and also because they are different than the conventional textile fabrics. The most common definitions used nowadays are those by the Association of the Nonwovens Fabrics Industry (INDA) and the European Disposables and Nonwovens Association (EDANA). Recently had been proposed to the International Standardization Organization by EDANA and INDA [85] the following definition for nonwovens - nonwoven is a sheet of fibres, continuous filaments, or chopped yarns of any nature or origin, that have been formed into a web by any means, and bonded together by any means with the exception of weaving or knitting; felts obtained by wet milling are not nonwovens; wetlaid webs are nonwovens provided they contain a minimum of 50% of man-made fibres or other fibres of non vegetable origin with a length to diameter ratio equals or superior to 300, or a minimum of 30% of man-made fibres with a length to diameter ratio equals or superior to 600, and a maximum apparent density of 0.40 g/cm^3; composite structures are considered nonwovens provided their mass is constituted of at least 50% of nonwoven as per to the above definitions, or if the nonwoven component plays a prevalent role. Figure 2.16 shows an example of a nonwoven structure.

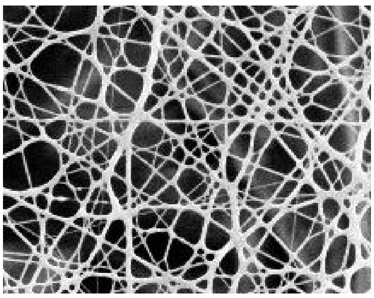


Figure 2.16 – Nonwoven structure

(*Source*: www.kalpaperchem.com/product-testing.htm)

Nonwovens production is divided into web formation and bonding. The web formation is further differentiated into four processes: hydrodynamic, aerodynamic, mechanical and spunlaid web formation. Regarding to bond process this is either done mechanically, thermally and chemically [50].

There are three types of mats which are used as reinforcement: chopped yarns mats (or fibre/filaments), continuous yarns mats (or yarns/filaments) and superficies mats. Nonwovens which are more appropriate to use in advanced composites are the fibres mats, nonwovens stitch-bonded, adhesively bonded and the xyz nonwovens (3D) [20, 28].

A huge advantage of theses structure is the low cost of manufacture because there is no need for material handling and the ability to produce materials of special properties in less time and at reasonable prices.

Nonwovens find numerous applications namely in civil construction. Important areas where nonwovens can replace traditional textiles are for instance geotextiles, materials for building, among others [50].

2.3.4.3. 3D fibrous structures

3D structures were developed in order to overcome one 2D structures drawback, mainly the low interlaminar resistance. According to *Gries* [55] 3D fibrous structures present three directions in yarn architecture and/or textile architecture, regardless of whether it is made in a one-step-process or multiple-step process. Yarn architecture is the yarns arrangement in the level of textile while, textile architecture is related to the fibrous structure geometry. Textile architecture is defined as 3D, if a volume is formed and/or embraced by the textile, regardless of the number of yarn systems and the so-created yarn architecture. While one-step-process leads to the production of near-net-shape textiles products in a single production process like, 3D warp knitting or 3D braiding, the multiple-step-process allow the production of near-net-shape textiles products in multiple production processes like, warp knitting and transforming or weaving and sewing. Near-net-shape is a textile architecture which has a profile similar to the final product and usually is a term used in the field of fibre reinforced materials such as, fibre reinforced polymer (FRP) or textile reinforced concrete (TRC). When compared 2D fibrous structures, 3D structures present high mechanical properties in *x*, *y* and *z* directions. These structures can be produced on special machines which are already developed. Nowadays there is a wide range of 3D structure which can be accomplished [39, 50, 51].

The 3D structures performance may be design due to: possibility of having three fibre directions (*x*, *y* and *z*) and thickness up to 2,54 cm), ability to use of using almost all high-performance fibres, such as glass, carbon, aramid fibre among others and possibility to make net shapes. Thus, they offer several advantages like, fibres configuration flexibility, structural integrity, continuity along all over 3D structure, adaptability, low weight, among others. On the other hand they improve fibrous structure properties in third dimension namely in interlaminar shear and strength in thickness direction as well as the delamination resistance. Mechanical properties like impact, insulating and acoustic resistance are also enhanced due to fibres presence in the third dimension [52].

There is not a simple way to classify 3D fibrous structures once it is necessary to consider several parameters such as, shape, dimension, fabric construction, fibres density and linear mass among others. 3D fibrous structures are divided in three types: multilayer, sandwich or spacer and performs near-net-shape structures. 3D multilayer structures present at least two surfaces (superior and inferior surface) and a layer which is between both surfaces. 3D perform or near-net-shape structures can be produced through planar fibrous structures deformation in order to get the desirable geometry or through perform structures production related to modified conventional equipment. Those structures besides providing homogeneous properties to the composite, due to the continuous reinforcement provided by the fibres, reduce waste materials and eliminate operations like sewing and cutting. 3D sandwich or spacer structures are composed by two layers connected to a yarn/filament system or structure oriented in third dimension, whose main features are high impact and delamination resistance, high stiffness and good insulating and acoustic properties. [39, 51, 52]

According to the textile production technique it is possible to have different types of 3D structures that are described as follows. Textiles production techniques usually used are weaving, knitting and braiding. However, it is possible also to use to nonwovens production techniques. 3D nonwovens or nonwovens spacer such as Kunit and Multiknit, perpendicular-laid nonwovens (Santex Wavemaker, Struto and Napco) are an advance, not only for economic reasons. However, once they are a relatively recent development, there is only a small amount of published information on their process production, mechanical properties and potential applications [57, 58, 88, 89, 90].

2.3.4.3.1. 3D woven structures

3D fibrous structures can be produced using to weaving technique. 3D weaving is a variation of conventional weaving (2D) placing yarns in the third direction (thickness).

3D woven fabrics are one of the most important due to their effective consumed volume in the future. Several 3D weaving structures can be accomplished using special equipment. The simplest is when warp is crossed by two sets of wefts (Figure 2.17a). It is also possible to produce a 3D structure where multilayer warps cross the material providing an angle of 45^0 in *x* and *y* directions and weft yarns crosses between the warp providing the *z* direction (Figure. 2.17b) [39].

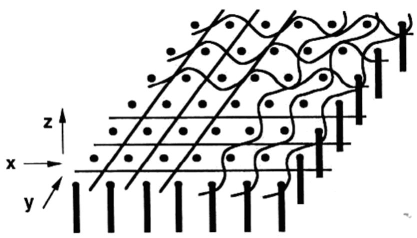
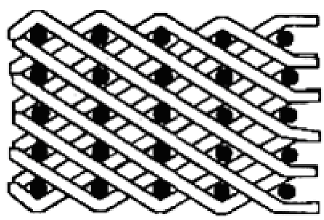
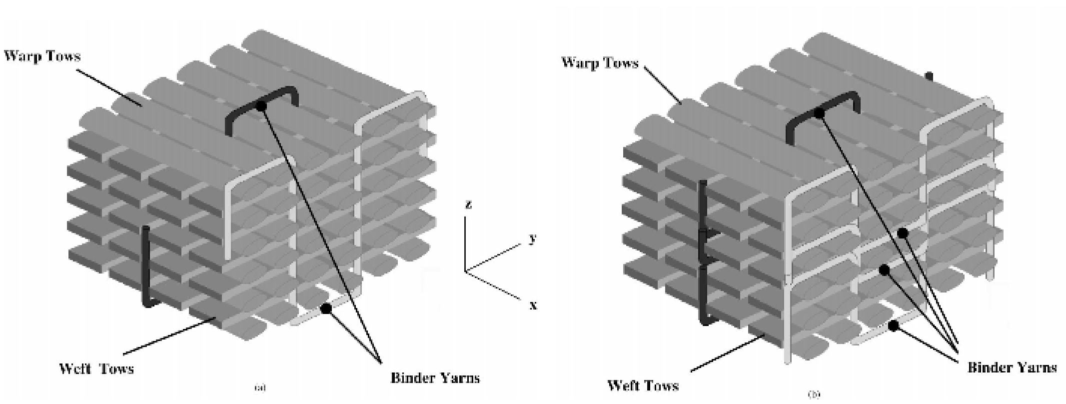


Figure 2.17 – (a) 3D weave, the simplest structure [39]



(b) Multilayer 3D weave with x/*y* warp direction and *z* weft direction [39]

One important advantage of this technique is that performs for a composite component with a complex geometry can be made to the near-net-shape leading to this way to, a great reduction on the component cost and waste material, the need for machining and joining, and the amount of material handled during lay-up. Also, performs can be made on standard industrial weaving looms used for producing 2D fabrics by making minor modifications to the equipment, which minimizes the costs once it is not required expensive custom-built looms to produce 3D woven preforms. Another advantage of 3D weaving is that wovens with a wide variety of fibre architectures can be produced with controlled amounts of binder yarns for the through-thickness reinforcement. Two of the most common architectures are the orthogonal and layer interlock weaves (Figure 2.18) [87].



(a) (b)

Figure 2.18 – (a) Orthogonal and (b) layer-interlock interlock woven fibre architectures commonly used in 3D woven composites [87]

Building industry has used 3D woven glass composites in a couple of niche applications. An example is the I-beams made with a 3D woven composite used in the roof of a ski chair-lift building in Germany. The main reason for its use is related to the difficulty in transporting and lifting heavy steel beams at the building site. Therefore, lighter 3D woven composite beams were used which demonstrated cost savings and improved performance over steel and conventional composite beams. The only other civil infrastructure application for a 3D woven composite has been for manhole covers in some petrol station forecourts [87].

2.3.4.3.2. 3D braided structures

Another possible textile technique which could be used in 3D structures production is braiding. The basic 3D braiding principle consists in mutual yarns intertwining. Generally braids are produced in a tubular form of biaxial yarns direction. Through the introduction of longitudinal oriented yarns into the structure it is obtained a 3D axial braid. Moreover, in the centre of the tubular braid, additional fibres called axial fibres can be inserted [39]. 3D braided structures present several advantages such as, higher levels of conformability, drapebility, torsion stability and structural integrity, which make it possible to produce composite structures with geometries to the near-net-shape. This feature can reduce manufacturing cost considerably once the amount of fabric handling and waste material is reduced. 3D braided composites also have higher delamination resistance and better impact damage tolerance [87]. The braiding technique can produce a wide range of preforms for composite reinforcements one being one the rod shape.

Despite the above advantages, the applications for 3D braided composites have been limited for several reasons. One major limitation is related to the maximum preform size which is determined by the braiding machine size, and most industrial machines are only able to braid preforms with a small cross-section (under 100 mm in width). Another problem is that many 3D braiding machines are still in a research and development stage, and only a few machines are presently able to commercially manufacture preforms. 3D braiding machines are also slow, and as a result, 3D braids cannot presently compete with 2D braids and laminates on a cost-saving basis [87, 90].

The current developments on the 3D braiding equipment are limited and therefore their costs are extremely high when for example compared to 3D weaving.

3D braided structures will remain limited until the issues mentioned above are solved. Despite these problems, in building industry a variety of components have been made that clearly illustrate the versatility of this textile process. 3D braiding has been used to C, J, I and T-section I-beams (Figure 2.19), bifurcated beams and connecting rods.

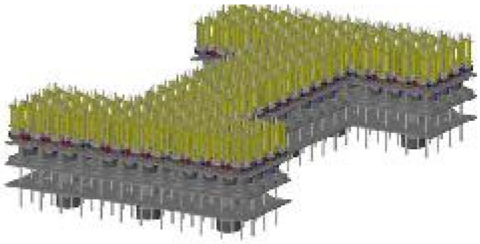


Figure 2.19 – Example of a braider scheme to produce 3D braided cross section shape developed by 3TEX [91]

Braided reinforced composites rods for concrete reinforcement (Figure 2.20), were developed at University of Minho. Advantages like excellent corrosive resistance, mechanical properties similar to steel, high strength-to-weight (10 times higher than steel), excellent fatigue resistance, nonmagnetic properties and low thermal expansion make them an alternative building construction material to steel [34, 35, 60].

Figure 2.20 – Braided composite rods and beam produced with braided reinforced composite rods after testing [60]

2.3.4.3.3. 3D knitted structures

Although, considerably research work has being done on conventional knitted reinforced composite, rather is known regarding to the 3D knitted structures being the least understood of 3D structures. These structures either can be produced by warp or weft knitting technique. Their use in composites is limited once the loop formation leads to a low tenacity. This drawback can be overcome through a yarn reinforcing insertion on the structure in directions where are applied the highest loads. Due to knitted specific properties like, malleability, drapebility and the high production process capacity, the applications have becoming more important and attractive for the composite industry.

There are two types of 3D knitted structures currently available, which are broadly categorised as spacer and near-net-shape structures.

Weft knitted fabrics are produced in electronic flat knitting machines or in electronic circular knitting machine. Resorting to the flat knitting machines is possible to produce 3D knitted near-net-shape or spacer structures while double knit electronic circular knitting machines allows the production of spacer structures.

Regarding to the warp knitted fabrics, the production flexibility and the ability of the electronic looms new generation for the near-net-shape production, have been the most explored aspect in the structures development for technical applications. On the other hand, the warp-knitted fabrics combine production technological advantages of weft knitted fabrics and wovens. Warp knitted fabrics' weaving is a production process quite flexible, which allows the production of stable or elastic, planar or tubular structures. This production process feature makes these structures more suitable for technical applications than the weft knitted fabrics.

Warp and weft knitted spacer fabrics continue to find new and novel product applications and it is generally recognised that spacer fabrics will be extensively used in the future in a wide range of products, mainly due to an extremely wide range of possibilities available to tailor make their aesthetical, functional and technical properties for niche applications [89, 90].

3D warp knitted spacer or sandwich structures

Warp knitted spacer or sandwich structures are composed by two separately fabric layers, top and bottom, interconnected by a third one oriented in the third dimension creating a three dimensional structure. Figure 2.21 and 2.22 illustrate the scheme of a warp knitted spacer and some examples. Both fabric layers can be produced using different types of materials and have completely different structures. Usually the top and bottom fabric layers are connected to each other mostly by monofilaments that either can fix both directly or space them apart. This type of configuration allows heat and moisture transfer, makes the structure lighter and confers good acoustic and insulating properties. Typically, spacer fabrics can be from 1 to 15 mm thick, with the two faces being from 0.4 to 1 mm thick. The major single feature of warp knitted spacer fabrics is that virtually any thickness can be obtained, depending upon the type of machinery used and the type of yarns and structures used [52, 53, 87, 88].

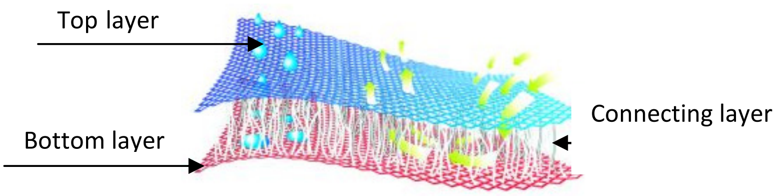


Figure 2.21 – Scheme of warp-knitted spacer

(*Source*: http://www.inteletex.com/FeatureDetail.asp?PubID=27&NewsId=191)

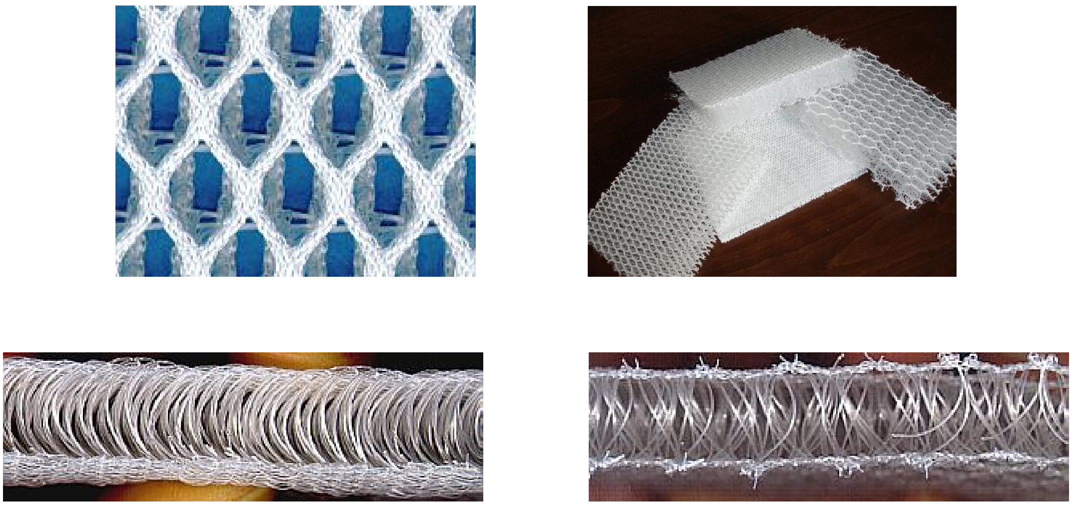


Figure 2.22 – Warp-knitted spacer separated by filaments

(*Source*: http://www.liba.de and www.karlmayer.com)

The most important characteristics of these structures are: lightness, flexibility, high stiffness and bending, excellent acoustic and insulating properties and the possibility of having different thickness and compression values. However, the main drawback of these structures is their weak delamination resistance once an impact in the structure can cause the separation between the top and bottom layers and the interconnecting layer. A solution to solve this problem consists in the use of double face structures being more difficult delamination occurs. This double face structures are normally produced in double-bed Raschel knitting equipment [51, 52, 53].

Spacer preforms (Figure 2.23) are produced on double-bed Raschel machines by knitting the top and bottom skins simultaneously on each needle bed. [87].

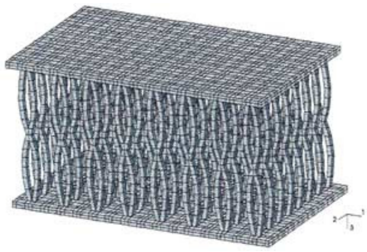


Figure 2.23 – Spacer preform scheme [51]

Warp knitted spacer structures are used in a wide range of applications being one of them civil engineering namely, in geotextiles and composite structures reinforcement. An area where these structures are being used is in thin sheet cement components, which includes for example wall panels, claddings and exterior siding.

In the last years application of warp knitted spacer fabrics as reinforcing of concrete applications has been searched [54, 55, 91]. For this application spacer provides reinforcement in the third direction, which has the advantage of providing an armour system that can be easily placed into a mould and infiltrated to its full thickness by a matrix in one step, and at a defined positioning of the two outer layers. According to *Mecit* [91] the third direction reinforcement provides shear resistance. When the reinforcement used in cement applications has a combined high strength and high elastic modulus, failure of the composite is often controlled by shear or interlaminar shear (between the layers of reinforcements) instead of bending so, reinforcement in the third direction is needed. In addition due to the easier construction of spacer structures is possible to reduce costs on the production. In order to produce warp knitted spacer structures for concrete applications, in the Institut für Textiltechnik (ITA), RWTH Aachen University, Germany, Raschel equipment have been modified with weft and warp insertion systems. Using this equipment, also *Roye and Gries* [53] developed warp knitted spacer structures for reinforcing cement products and concluded that it is relatively easy to produce wide structures with the desired properties for cement and concrete applications and that the structure width and thickness can be adapted easily to the exact size of the concrete application which is advantageous in technological and economical terms. Figure 2.24 shows two applications of this structures realized in Germany [54].

Figure2.24 – 3D sandwich-25 covered with fine grained concrete on the surfaces and TRC facade elements at RWTH Aachen University respectively [54].

3D knitted near-net-shape structure

3D knitted near-net-shape structures were first made during the early 1990´s. Near-net-shape knitting can be performed by a two-bed weft knitting machine, however additional needle beds are required for producing 3D [87].

Karl Mayer a textile machinery manufacturer developed an equipment named HighDistance® which allows 3D near-net-shape production. HighDistance® allows, a variable production on spacer heights from 20 mm up to 65 mm, at the moment impossible to produce, the incorporation of functions in determinate place providing maximum compression resistance and production of shapes which coincide with the final components (preforms or near-net-shape). Figure 2.25 shows some examples of 3D near-net-shape produced with this equipment [56].

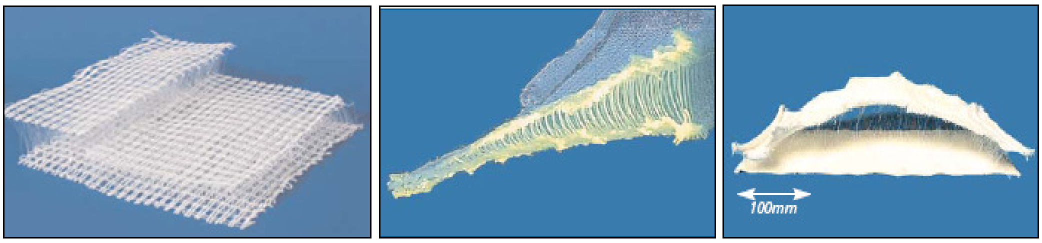


Figure 2.25 – 3D knitted near-net-shape structures

3D weft knitted spacer structure

Weft knitted spacer fabrics can be produced on circular double jersey machines as well as on electronically controlled flat machines. The major advantages obtained with these structures are: plain colour, design and surface texture effects can be produced on the face of the fabric knitted by the cylinder needles (Figure 2.26); and shaped and true 3D structures can be produced on electronically controlled flat machines.

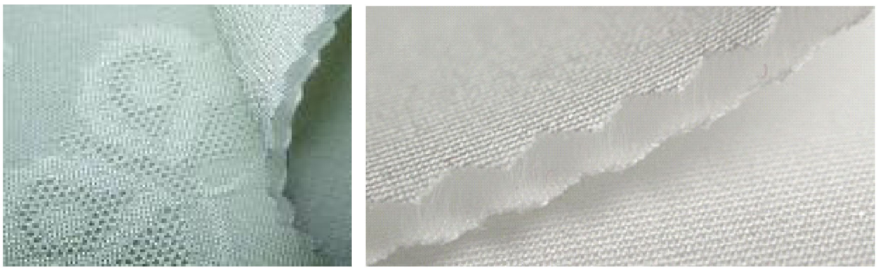


Figure2.26 – Jacquard spacer – weft knitted mattress cover fabrics

(*Source*: www.inteletex.com/FeatureDetail.asp?NewsId=3417)

Despite the above mentioned benefits, weft knitted spacer fabrics present limitations such as: spacer thickness is normally limited to 2 and 10 mm range and spacer fabric basic structure is limited to either knitting the spacer threads on the dial and tucking on the cylinder, or tucking the spacer threads on the dial and cylinder needles [87].

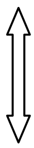
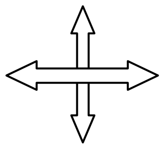
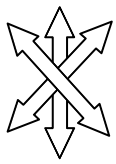
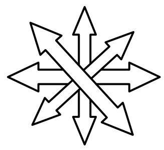
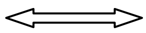
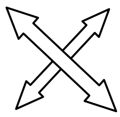
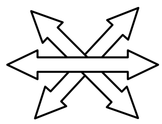
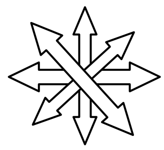
Due to the production process the areas of application of these structures are not as wide as for warp knitted spacer fabrics although they present more or less the same.

2.3.4.4. Directionally oriented structures (DOS)

In order to enhance structures mechanical properties, it is possible to introduce in the ground fibrous structure, reinforcing yarns in the directions of the main loads applied to the material. These structures known as directionally oriented structures are two dimensional structures (2D) but with the particularity of possessing reinforcing yarns. Thus, it is possible to produce several different DOS structures reinforced in the desired direction, according to the envisaged application.

DOS can be classified according to the number of reinforced directions in: monoaxial, biaxial, triaxial and multiaxial structures. Table 2.5 summarizes the DOS structures.

Table 2.5 – DOS classification according to the reinforced direction

Monoaxial structure	*Biaxial structure*	*Triaxial structure*	*Multiaxial structure*
 Warp reinforced	 Warp and weft reinforced	 Warp and diagonal directions reinforced	 Warp, weft and diagonal directions reinforced
 Weft reinforced	 Diagonal directions reinforced	 Weft and diagonal directions reinforced	 Warp, weft and diagonal directions reinforced

2.3.4.4.1. Monoaxial or unidirectional structures

Monoaxial structure is presents high number of parallel fibres oriented in a preferably direction. Usually fibres are oriented at 0^0 along warp direction or at 90^0 along the weft direction [20]. The great advantage of this structure is place straight and uncrimped fibres in the amount required. However, handling is a drawback. There are various methods to keep primary fibres in position in a monoaxial fabric including weaving, stitching, and bonding [24]. Figure 2.27 shows two examples of this type of structure.

(a) (b)

Figure 2.27 – (a) monoaxial woven tape (b) monoaxial stitched woven [61]

(*Source*: www.seldom-srl.com)

Warp or weft knitting technologies may also be used to produce monoaxial fabrics. In the following Figure 2.28 it is possible to observe those structures [24].

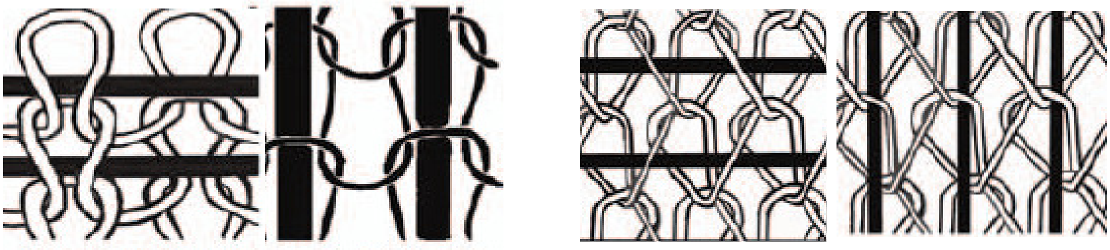
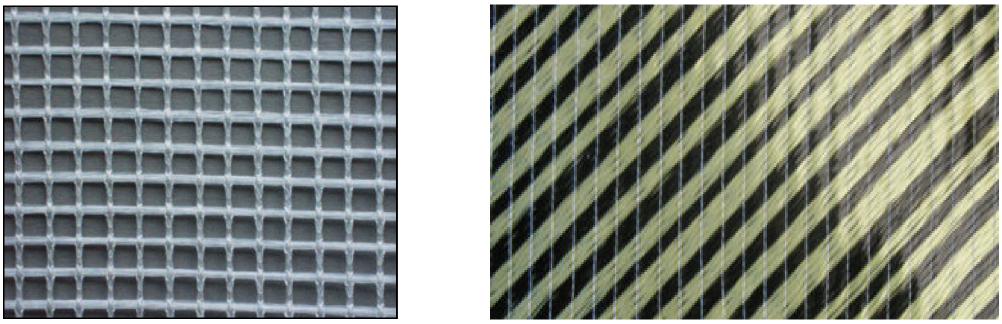


Figure 2.28 – Monoaxial weft knitted and warp knitted structures respectively [62]

2.3.4.4.2. Biaxial structures

Biaxial structures are reinforced in warp and weft directions by different ways. The characteristic crimp of yarns is removed and the yarns are straight and settled in layers placed at 90^0 and attached by one linking yarn that represents 10% of total. There are some criterions to choose the right fabric: easy handling and placing in site, mass per unit area (g/m^2) and thickness regularity, continuity of the reinforcement and ease of impregnation [20]. Biaxial structure may be used in several fields like in building construction and also composites made of heavy-duty yarn materials namely fibre glass, carbon, aramid for the manufacture of fibrous/plastic nonwovens [63].

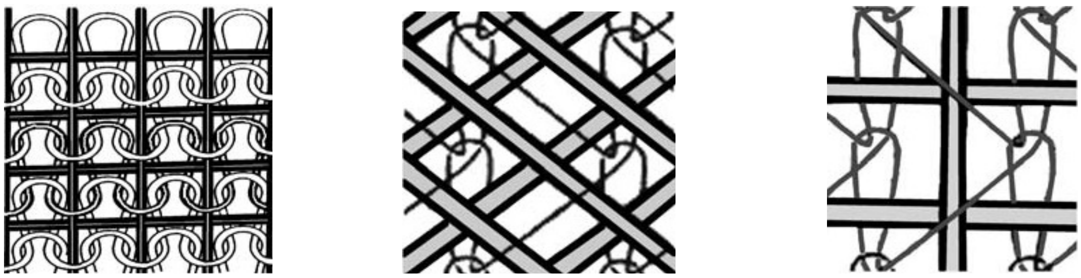
The following Figure 2.29 illustrates biaxial woven structures reinforced in $0/90^0$ (Figure 2.29a) and $+45^0/90^0$ directions (Figure 2.29b). It is possible to used different types of materials in the structures as it can be seen in Figure 2.29.



(a) (b)

Figure 2.29 – Woven biaxial structure in different directions [61]

Besides biaxial wovens, it is also possible to reinforce weft and warp knitted structures in two different directions as it can be seen in Figure 2.30.



(a) weft knit (in-lays $0/90^0$) (b) warp knit (in-lays $+45/-45^0$) (c) warp knit (in-lays $0/90^0$)

Figure 2.30 – Warp and weft knitted biaxial structures [62]

2.3.4.4.3. Triaxial structures

These fabrics are reinforced in diagonal directions being composed by two yarns systems of warp at $\pm 60^0$ and one weft yarn. The main objective of the reinforcement is to withstand applied effort in those directions [20]. Figure 2.31 shows a triaxal woven structure.

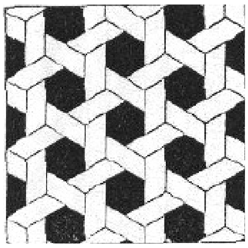
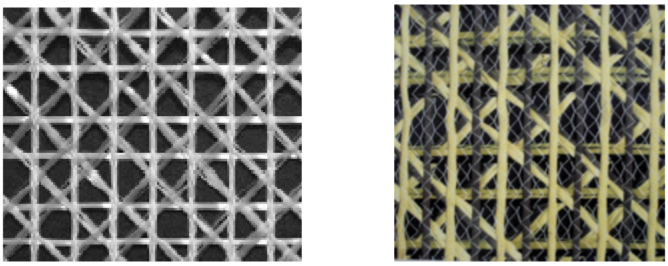


Figure 2.31 – Triaxial woven structure [39]

Due to their specific arrangement, these structures cannot reach higher thread densities. Triaxial structures present exceptional mechanical properties in several directions and high shear resistance due to the fact the interlacing points are fixed into the fabric [39].

2.3.4.4.4. Multiaxial structures

In recent years, multiaxial structures have found a place in the construction of composite components. The conventional structures usually provide biaxial reinforcement (warp-weft). However, those structures present disadvantages when a load is applied in diagonal directions due to the material anisotropy. One way to overcome this problem consist in lay reinforcing yarns at $+45^0$ and -45^0 leading to multiaxial structures that provides four reinforcing directions giving an higher isotropic behaviour to the material. The main advantage of these structures is the complete use of yarn mechanical properties, although the same feature could be a disadvantage when loads are applied outside the plane causing delamination. Considering this drawback other multiaxial structures were developed using warp knitting technology in order to interlace reinforcing yarns [52]. Two examples of multiaxial structures are showed in Figure 2.32.



(a) (b)

Figure 2.32 – Multiaxial structures: (a) stitch-bonded multi-axial structure (b) multiaxial warp knitted structure [69, 61]

Figure 2.33 illustrates the scheme of a multiaxial warp knitted structure. This structure is defined by a warp knitted structure whose yarns straight and load bearing are introduced in a fabric structure in four directions, warp, weft and diagonal directions. As mentioned *Demboski* and *Bogovea* [39], one set of machine operations lays down sheets of reinforcing yarns and then these are passed into the knitting zone, where they are held together by the stitches of knitting yarns. If the aim is to reinforce composite to withstand forces in all directions this structure is particularly suitable.

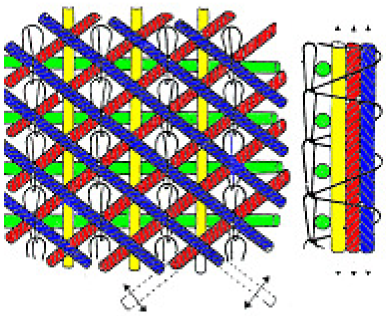


Figure 2.33 – Multiaxial warp knitted fabric with oriented yarns in four directions [39]

2.3.4.5. Hybrid Structures

Hybrids structures are the result of the combination of different kinds of structures with the main purpose of balancing some characteristics or weakness of individual materials being used in specific applications. From the synergy of both structures properties, results a structure with improved properties [20, 51]. Most of the hybrids are found in $0/90^0$ direction woven fabrics, it is possible to apply the same principle to

$0/90^0$ stitched, monoaxial and multiaxial fabrics [24]. Usually this type of structures is produced through warp knitting technologies combining the properties of two structures manufacture processes in one [51]. Warp knitting technique may be used for example to connect nonwovens with directionally oriented knits in an unique operation. The connection is given exclusively in the loop crossing points, which allows maintaining the work amplitude of knit and preserves nonwovens characteristics.

2.4. CONCRETE

2.4.1. Introduction

Concrete is one of the most worldwide used construction materials and due to its properties it is an attractive building material. This material can provide an aesthetic finish and structural capabilities [30]. If used conveniently structures made by concrete are extremely durable [11]. There are several reasons for their use, namely such as: high compression resistance, durability and environmental stability, fire resistance and atmospheric agents' resistance, easy of application and moulding possibility, low cost, excellent behaviour under dynamic and static loads, and exploitation of materials that exist in nature and in local origin and moderate costs of conservation.

Concrete is a heterogeneous material whose properties depends on the individuals properties of its components, as well as its compatibility [31]. Generally, the most common composition of concrete is: air, fine and coarse aggregates, cement and water (Figure 2.34)

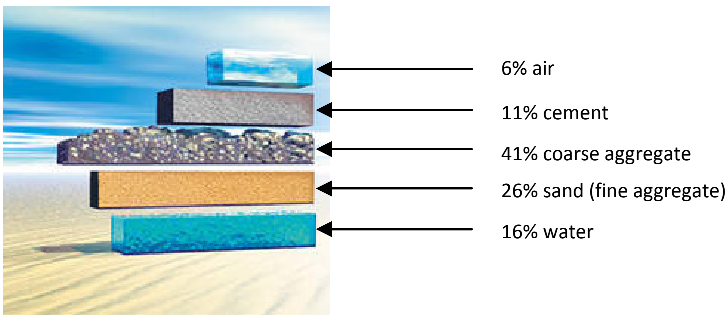


Figure 2.34 – Common concrete composition [31]

The paste, composed of cement and water, coats the surface of the fine and coarse aggregates. Through a chemical reaction called hydration, the paste hardens and gains strength to form the rock-like mass, known as concrete. The key to achieve a strong, durable concrete rests in the careful proportioning and mixing of the ingredients [32]. A properly designed concrete mixture will possess the desired workability for the fresh concrete and the required durability and strength for the hardened concrete. The concrete components influence the properties of concrete [32]. The type and size of the aggregate mixture depends on the thickness and purpose of the final concrete product. The fine aggregate properties depend on their natural state and of the production process. If they do not have the right size and the right nature, properties such as, workability, resistance, elasticity modulus, density and durability, will be influenced [31]. Water can also influence the concrete behaviour. Excessive impurities in mixing water not only may affect setting time and concrete strength, but also may cause efflorescence, staining, corrosion of reinforcement, volume instability, and reduced durability. Nevertheless, other components can be added with a main objective, to improve the concrete properties [32].

Concrete can be of different types like fine grained concrete, self-compacting concrete or hardened concrete. The first one is produced and used either as structural concrete either as isolation, being in this last e case the thermal conductivity an important issue which increases with the reduction of density. This type of concrete possesses properties, such as, reduction of weight, improvement of some physical properties and higher durability, which makes it very interesting for some applications like, large constructions, bridge (anchorage, arch, beam, etc), box culvert, building, concrete filled steel column, tunnel (lining, immersed tunnel, fill of survey tunnel), dam (concrete around structure) and concrete elements (block, water tank, culvert, wall, slab and segment [31, 74].

2.4.2. Steel reinforced concrete problems

As mentionetd by *Pandey* and *Banerjee* [33], corrosion of reinforcing steel in concrete has been recognized as a serious problem through the world. Due to its inherent low tensile strength, however, concrete requires reinforcement in applications where significant tensile stresses are required, in order to maximize its load-carrying capability and improve its toughness. Conventional concrete technology uses composite theory to optimize the effects of various combinations of matrix materials, graded aggregates, and reinforcement materials (example continuous rebar reinforcement and fibres) on overall performance and properties.

Steel, used for concrete reinforcement, is normally protected due to the passivation that consists in a stable membrane mainly of gamma – Fe_2O_3 which prevents corrosion. However, continuous exposure to corrosive environmental conditions added with steady deterioration with time due to thermal effects, seepage and to constant and high mechanical solicitations, lead to corrosion and failure of concrete structure and consistent fall of life service. Figure 2.35 shows the effects of corrosion and chlorine ions on the concrete structures.

Figure 2.35 – Chlorine ions action in railings wall and steel reinforcement corrosion

(*Source*: corrosion.ksc.nasa.gov/corr_forms.htm)

As previously mentioned one of the biggest problems associated to reinforced steel concrete deterioration is related to corrosion, caused mainly by two factors, carbonation which is the reaction with carbon dioxide and the action of chlorides. Although concrete is inherently a tough durable material many types of reinforced concrete structures are subjected to corrosion damaged initiated when oxygen and chlorides penetrate the concrete and contact the reinforcing steel inside [33, 34, 35] The first problem consists in the progressive reduction of concrete alkalinity due to reaction between the carbon dioxide from the atmosphere that throughout the time neutralises the alkaline properties of concrete, slowly causing deterioration because of lower pH. When the concrete covering the armours loses its alkalinity, the oxide layer protecting the steel may be destroyed, thus leading to the development of the "stack effect", i. e., the formation of electric currents which are responsible for the corrosion of the steel [35]. The second problem is related to the chlorides and bromides action, the intrusion of these aggressive agents destroys the passiving films, exposing the steel to a rapid corrosion if oxygen and moisture are present [11, 33].

After corrosion starts it tends to propagate and the rust takes up more space than the original steel causing pressure within the concrete leading to cracking and spalling. Other problems can be associated to the corrosion, leading to the necessity of rehabilitating and/or strengthened the concrete structure. The reasons for that needs are:

- construction age with the consequently materials deterioration;
- durability impediments, due to the armour corrosion caused by the chloride ions penetration;
- carbonation and action of sulphates;
- exposure to accidental actions, for instance, fires, explosions, vandalism, earthquake among others;
- mistakes in the planning or execution of construction project;
- bad quality of the materials used in the structures construction;
- bad intention of the constructor;
- aggravation in the acting load value due to modification in the construction usage or regulations.

Corrosion can occur in different ways, can be localized, generalized or uniform and localized under tension [11]. According to *Pandey* and *Banerjee* [33], several measures can be taken to prevent corrosion, namely:

- selection of concrete materials and design elements that will provide maximum protection of the reinforcing steel;
- coating the reinforcement steel with metallic or non-metallic materials;
- use special concrete treatments, admixtures and coatings to reduce the possibility of corrosion on the steel reinforcement;
- installation of a cathodic protection system;
- use and maintenance of a corrosion monitoring system that will indicate when corrosion begins to affect the reinforcing steel or when corrosion is occurring and becoming a significant danger to the structure.

However, other solutions can be taken namely the search for new reinforcement materials. The choice of the form of concrete reinforcement can be justified by several reasons namely, the economical aspect, the possibility of easy and quick applications, design flexibility in terms of architecture, and the possibility of concrete lightweight elements production presenting high mechanical and durability performance.

Concrete is a building material, strong in compression but weak in tension, poor in crack opening and propagation and tends to be brittle. The weakness in tension and in crack opening and propagation can be overcome by the use of conventional rod made of steel or by alternative materials such as fibrous materials and structures. Once steel presents an huge drawback worldwide recognised corrosion, and although there are some treatments to outperform corrosion problem, none of them seem to be solution. Thus, a new concept of alternative reinforcement has been applied in order to overcome steel corrosion problem - *Fiber Reinforced Concrete* (FRC). FRC is concrete containing fibrous material which increases its structural integrity. Usually contains short discrete fibres that are uniformly distributed and randomly oriented. Fibrous materials include steel, glass, synthetic and natural fibres. FRC presents different features depending on, type of concretes, fibre materials properties, geometries, distribution, orientation and densities. The use of fibres alters the behaviour of the fibre-matrix composite after it has cracked, thereby improving its toughness, ductility and energy absorption. Besides the use of disperse fibres in the last years, research has been done in concrete reinforcement resorting to fibrous structures (wovens, knits, braids and nonwovens) once as an all-product they possess better properties than disperse fibres. There are several types of composites used for civil engineering applications namely Fibre Reinforce Polymers among others. A new concept in this field has been developed in recent years, *Textile Reinforced Concrete* – TRC [42, 64].

2.5. TEXTILE REINFORCED CONCRETE (TRC)

2.5.1. Introduction

The application of fibrous materials in several engineering sectors is nowadays of a very interesting development. As a synergy of fibre and fibrous structures technology developments, it is possible to produce advanced fibrous materials for many non-conventional applications. High demands on high performance properties such as strength-to-weight and modulus-to-weight ratios, durability, dimensional stability and on functions such as monitoring, flame-retardance, acoustic insulation, among others, make fibrous materials suitable for several civil engineering applications.

Fibrous structures namely, weaving, knitting and braiding have been recognized as a very attractive composite reinforcement due to the possibility of production performs, allowing fibre orientation, conformability and handling. Development and replacement of conventional construction materials, by better performance ones, is receiving a great deal of attention by the both textile and civil scientific community. The use of fibrous materials as reinforcement materials of cementitious matrices is one of its many applications that have gain new developments [36].

Concrete construction is facing a new challenge due to the deterioration of structures. Steel reinforced concrete is widely used in civil construction industry, being one of the most important composite materials. However, corrosion of steel reinforcement has been recognized as a serious problem throughout the world. Due to its inherent low tensile strength, concrete requires reinforcement in applications where significant tensile stresses will be realized in order to maximize its load-carrying capability and improve its toughness [34, 35, 36]. Due, not only to steel corrosion, but also to fatigue and other degradation agents, steel reinforced concrete service life is limited. In attempt to solve this problem, diverse techniques have been developed such as, galvanizing, epoxy coating, and others, but none of them seem to be viable as suitable solution to the corrosion problem [35]. Thus, in order to solve this drawback and improve the serviceability and performance durability and to reduce the corrosion problem of steel concrete reinforced structures a new approach to concrete reinforcement has been developed in the last years - *Textile Reinforced Concrete* (TRC). This new material which can be used in the reinforcement of concrete is an innovative construction material where fibrous structures are used to reinforce concrete in order to eliminate the corrosion process of steel reinforcement, among others.

Using the existing textile technologies it is possible to produce several types of fibrous structures with high-performance fibre namely, glass, carbon and aramid, in a way that fibrous structures present the ability to compete with steel on the production of reinforced concrete elements. Fibres are a good choice for replacing steel as reinforcement in the concrete. Advantages such as, excellent corrosive resistance, mechanical properties similar to steel, high strength-to-weight ratio (10 times higher than steel), excellent fatigue resistance, nonmagnetic properties and low thermal expansion are the reasons for using it. Several fibres are used for reinforcement, but usually are the high-performance fibres, such as carbon, aramid and glass, with higher preference due to their excellent mechanical properties such as, high tensile strength and stiffness. The fibrous material selection is made depending on the values of tensile strength and stiffness required for the composite material, although other requirements are taken into account like, elongation at failure, thermal stability, adhesion among fibres and matrix, dynamic and long-term behaviour, price and processing costs [25, 34].

Fibres and fibrous structures can be used as reinforcement of concrete in all most structures, due to their high strength weight-to-ratio, high modulus, easy handling and easy place in site. The main function of fibrous structures and fibres in composites is to hence or restores the strength and/or stiffness to the original structure. Thus, fibrous structures/fibres can be applied in:

- pillars: where they act as confining membrane surrounding the column which preserves the geometric shape of the column providing high strength load path through the stresses can safely be dissipated;
- walls: they are applied in the outer surface of the wall and their objective is to double the shear load carrying capability of the structure;
- beams: they are placed in beam underside, providing a load path for the increasing stresses to follow and prevents localization and the ensuing cracking which leads to failure;
- slabs: the application of textile on the side of the slab away from the load will lead to lessen deflections for a determinate load thus decreasing the likelihood of cracking [37].

TRC due to its features when used as concrete reinforcement, present several advantages when compared to steel namely easy handling, transportation and placing in site, excellent corrosive resistance and the ability of fibre orientation according to the final application. The use of TRC allows the production of thin and lightweight elements that are corrosion-resistant, durable, of low cost and with bearing capacities increased while its ductility can be significantly improved [36].

2.5.2. Concrete as a matrix for fibrous materials

The use of fibrous structures as reinforcement material of different types of matrices, namely cementitious is the result of science and engineering convergence.

For TRC material the matrix requires special demands relatively to the production processes, mechanical properties of the composite and durability of reinforcement materials. Therefore, the consistency of the matrix has to be adjusted to the fibrous materials properties, to their geometry and manufacturing processes. The matrix design will always be a compromise between all requirements regarding fresh, mechanical and durability aspects as well as economic aspects for industrial production of TRC elements.

Regarding to the matrix composition, it has to be chemical compatible with fibrous materials, suitable consistence for full penetration of the fibrous material reinforcement, as well as for planned production processes and finally mechanical properties for load carrying capacity of TRC. The mixtures will be different depending on the final application [29].

2.5.3. Textile reinforced concrete mechanical behaviour

Textile reinforced concrete (TRC) is a new and innovative composite material used for technical textiles applications whose development is based on the fundamentals of glass filament reinforced concrete with short filaments. These structures present similar behaviour to the fibre reinforced concrete (FRC). Due to the aligned fibres in the tensile load direction an increase of their effectiveness occurs. Moreover, the load–carrying capacity is higher than FRC with short fibre. All these advantages lead to a reduction on the costs. The load-bearing as well as deformation behaviour of TRC has not been study yet. The load bearing of TRC not only depends on qualities of the used material, bond behaviour between the structure and the concrete has to be considered.

Textiles are composed by yarns or rovings which are long fibres called filaments. These last ones are dividing into two different groups: the sleeve filaments which are in direct contact with concrete and presents better bond performance than the second group which is the core filaments that are stressed indirectly by the bonding due to the concrete protection by sleeve filaments. Besides the bonding behaviour between fibres and concrete the bonding between the filaments also has an important role.

Regarding to the mechanical behaviour the main difference between FRC and TRC is in their design philosophy at ultimate load. The first’s structures obtain their ductibility from the fibres to be pulled out of the matrix, so the pull out load is always lower than fibre length. TRC obtains their ductility from the fibre breaking strain.

The failure mechanism of TRC is not completely known. Recent studies can provide possible factors which can influence that mechanism [29]:

- fuzziness of the filament properties – mainly filaments strength and filament diameter in a certain point;
- damage of filaments during several production steps – textile manufacturing, composite manufacturing;
- bond properties between filaments and filaments depending on the sizing, secondary impregnation, yarn geometry, confinement/transverse pressure;
- bond properties between the filaments and the matrix depending on the sizing, secondary impregnation, matrix composition, yarn geometry, composite age and load history;
- filament adjustment that depends on yarn quality, fabric production and concrete technology;
- fibre orientation - angle between fibres and loading.

In a general way the failure mechanism of multifilament is very complex. Due to the rovings unhomogeneity on the cross section, a direct analogy to the bond behaviour of steel in concrete it is not possible.

Based in several investigations carried out in RWTH Aachen University in Germany, it is possible to confirm that load-bearing capacity is influenced by the interaction between internal and external bond of the yarns [29]. The filaments which are in direct contact with the matrix determinates the bonding behaviour once are responsible for the high bond strength but also because they are responsible for the damage on glass filaments due to alkalinity. Furthermore, textile fabrics composed by yarns with higher diameters present lower load-bearing than yarns with small diameter.

Many testing set ups were developed in special uniaxial tension testing using different types of fibres such as, PP, AR-glass and carbon. Several conclusions were taken [29]:

- coating or lamination of textiles seem to be reasonable to control directly the bond characteristics of the sleeve and core filaments;
- yarn orientation influence the behaviour of composite material;
- fabric production leads to a change on composite behaviour once the yarns during their production are modified in several manners; three parameters are responsible for those modification: the type of weave, stitch length and tension on yarns;
- the production of composite influences the strength: depending on the fabric used the strength can increase as well as can be reduced;

The mechanical qualities of TRC at the moment are not very well known due to their complexity. There are several parameters which influence the load-bearing TRC namely, material, amount, production process and orientation of textile reinforcement as well as by the fine concrete matrix. Although, it is possible to do some analogy with the steel reinforcement due to the inhomogeneous cross section of the rovings, the textile tensile strength cannot be exploited in the composite material TRC [29]. More studies needs to be done on this field by different perspectives to achieve the best performance of the TRC in the manner as it will be possible to use them in replacement of steel reinforcement in some specific applications.

CHAPTER III

DEVELOPMENT OF DIRECTIONALLY ORIENTED FIBROUS STRUCTURES

3.1. INTRODUCTION

Fibrous structures present several characteristics making them suitable as a concrete reinforcing material. They allow the reinforcement of concrete elements close to the surface in different load directions (slim cover).

From the several fibrous structures available only few are suitable for concrete reinforcement. Concrete reinforced with fibrous structures is named *Textile Reinforced Concrete* – TRC. The most important criterion for this type of fibrous structures in that an open structure with high displacement stability is required, once it is necessary a complete envolvement with the concrete itself. Wovens are suitable fibrous structures once they can fulfil these requirements. These fibrous structures of full or half cross weave are mostly used to stop crack propagation and with only one layer it is possible to reinforce in multiple load bearing directions. This type of structures allows the production of thin and lightweight concrete elements. The use of glass fibre or other synthetic fibres do not corrode and a minimum cover of concrete is. So, it is possible to reduce the concrete element thickness up to 75% and the weight up to 80%. Moreover TRC offers reduction on transportation and assembly costs besides representing an aesthetic alternative [29, 69].

The interrelation between fibrous structure and composite performance is significantly more complicated than fibrous structures within polymer binders and composite.

In this chapter it is described the experimental work carried out in the development of directionally oriented fibrous structures and respective characterization. The chapter is divided into:

- experimental plan;

- materials characterization;
- development of directionally oriented fibrous structures.

3.2. EXPERIMENTAL PLAN

The aim of the present work consists in the development of fibrous structures namely directionally oriented fibrous structures (DOFS) being able to replace steel and overcome its main drawback – corrosion – in concrete reinforcement. Thus, it is intended to produce different types of DOFS with different roving fibres orientations, in order to study their application in the replacement of steel in lightweight concrete elements reinforcement. The experimental plan has been established in order to understand the mechanical properties of the woven structure used as base to produce the DOFS. It was done the woven fabric structural characterization as well as the study of its mechanical properties.

Several directionally oriented fibrous structures were developed varying two parameters, rovings linear density (tex) and structural density (roving/cm). The orientation selected for these set of samples were $0/90^0$. A pre-stressing frame was developed to allow the right placement of the DOFS during concrete slabs production.

3.3. MATERIALS CHARACTERIZATION

3.3.1. Rovings fibres

Rovings are an assemblage of several hundred of single filaments with small diameters, kept joined even after their application. Rovings allow the reinforcing in the load direction, thus their ability to carry tensile and bending loads is considerably increased. The variation in strength and stiffness of the fibres rovings could be seen as an advantage allowing the development of materials with the required strength or stiffness in the direction in which these properties are required. Besides that, this type of geometry provides mechanical anchoring of the fibre to the cement matrix, resulting in a strong bonding by the penetration of the cement matrix in between the opening mesh.

E-glass fibre rovings were used to produce the directionally orientated fibrous structures (DOFS). The reason to select this type of high-performance fibre is related to its advantages:

- mechanical strength: glass filament has a higher specific resistance than steel, therefore the filament can be used to manufacture strand and develop good high quality composites;
- low weight, glass fibre presents a lower density, 2,56 g/cm^3 than steel which density value is 7,86 g/cm^3;
- good tensile and compressive strength;
- good stiffness and abrasion resistance;
- good electrical properties;
- high modulus;
- low thermal conductivity, this makes it possible to minimize thermal bridging and hence make considerable heat savings;
- high number of filaments perunit weight;
- incombustibility, once it is a mineral material is incombustible, does not propagate and maintain the flame and when exposed to heat does not release toxic products or smoke;
- compatible with organic matrices which enables it to be combined with resins as well as cement minerals matrices.
- due to its size and shape, it is possible to manufacture composites with thin sections that have good bending strength;
- improves concrete ductility/toughness;
- relatively low cost and commercially available;
- possibility of recycling [36, 38, 65, 66, 72].

Although, E-glass fibres are attacked by the cement alkalis, the choice of this type of fibre for the present work it is justified by the high ratio quality/price and also by the objective of the study, evaluation of directionally oriented fibrous structures mechanical performance. Besides, the period of time required for concrete casting is not enough long to attack glass fibre significantly.

3.3.1.1. Rovings mechanical properties

Usually the maximum tensile strength of a roving is not achieved mainly due to the brittleness of these fibres. These types of fibres are extremely sensible to defects by the materials. The number of defects existing in the material is proportional to its volume, i.e., a filament with a lower diameter can have superior strength than one with an higher diameter, or a filament with a lower length could be stronger than one with greater length. The strength of the filaments is also influenced by their diameter if not uniform along their length [70].

An internal proceeding was used to determinate rovings tensile strength once it was not available a specific standard. Testing's were performed using a tensile equipment, *HOUNSFIELD H100 KS* with the following testing parameters:

- Speed: 25 mm/min
- Distance between jaws: 250 mm
- Extensometer
- Samples dimensions: 2,5 x 30 cm
- Pre-load: 10 N

As E-glass fibre rovings surface is very slippery and their diameter is very small, common clamping jaws cannot fix it up to the equipment during the test. Thus, in order to avoid rovings slip and to fix samples in the jaws, resin was applied at the ends of the rovings. Figure 3.1 shows examples of samples prepared for testing.

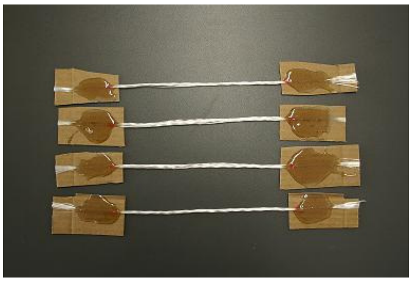


Figure 3.1 – Roving samples

Tests were performed on warp and weft rovings. Tables 3.1 and 3.2 show the results obtained for the tensile properties either for warp and weft rovings.

Table 3.1 – Mechanical properties of warp rovings

	E Modulus (MPa)	***Tensile strength (MPa)***	***Max Load (N)***	***Extension Max (%)***	***Tenacity (cN/Tex)***
1	10718	219,4	760	1,932	0,189
2	15342	209,9	727	1,602	0,197
3	7793	219,4	760	2,12	0,186
4	7740	251,2	870	2,16	0,164
5	6653	213,7	740	2,184	0,180
AV*	9649,2	222,72	771,4	1,9996	0,183
SD**	3522,00	16,42	56,88	0,24	0,01
CV***	36,50	7,37	7,37	12,17	6,73

*AV = average; ** SD = standard deviation; ***CV = coefficient of friction

Table 3.2 – Mechanical properties of weft rovings

	E Modulus (MPa)	***Tensile strength (MPa)***	***Max Load (N)***	***Extension at Max (%)***	***Tenacity (cN/Tex)***
1	11424	246,3	853	1,76	0,157
2	7536	222,3	770	1,888	0,132
3	8334	210,8	730	1,8	0,172
4	4967	194,4	673	1,98	0,107
5	11288	213,7	740	2,32	0,185
AV*	8709,8	217,5	753,2	1,9496	0,1507
SD**	2717,61	19,01	65,93	0,22	0,03
CV***	31,20	8,74	8,75	11,48	20,76

*AV = average; ** SD = standard deviation; ***CV = coefficient of friction

From the results obtained, was calculated for each warp and weft rovings the tenacity and respective extension. The roving tenacity is the ratio of its breaking load by the linear density in *tex* being normally expressed in *cN/Tex*. The extension is the elongation in percentage relatively to the initial sample length.

Either for E-modulus, tensile strength and tenacity, warp rovings performs better when compared to weft rovings. The CV values are high due to the specific features of glass fibre. When the rovings samples are tested, some filaments are already damaged due to handling. Besides they do not work at the same time during the testing once they are not all completely stretched. When load is applied the outer filaments deform earlier and larger than inner ones. In some cases when the test is finished it is seen that not all filaments broke and the final tensile strength was not achieved. The modulus of elasticity obtained is far from what is presented in the literature, 70-80 GPa.

Figure 3.2 and 3.3 present the tenacity *vs* extension curves for the rovings tested. The results obtained for warp and weft rovings are relatively similar. Analysing both tenacity vs extension curves in both cases it is possible to divide the roving tensile behaviour in three stages:

- Stage 1: corresponds to the linear range where the tenacity is proportional to the extension; this stage is also characterized by the capacity of fibre rovings to absorb energy without permanent deformations; for warp and weft rovings this stage is very similar.
- Stage 2: corresponds to the maximum force which fibre rovings can support before the rupture; tensile strength is achieved; in general warp rovings present higher values of tenacity than weft rovings at this stage;
- Stage 3: for warp and weft rovings there is a decrease on the tenacity after the tensile strength till the total failure.

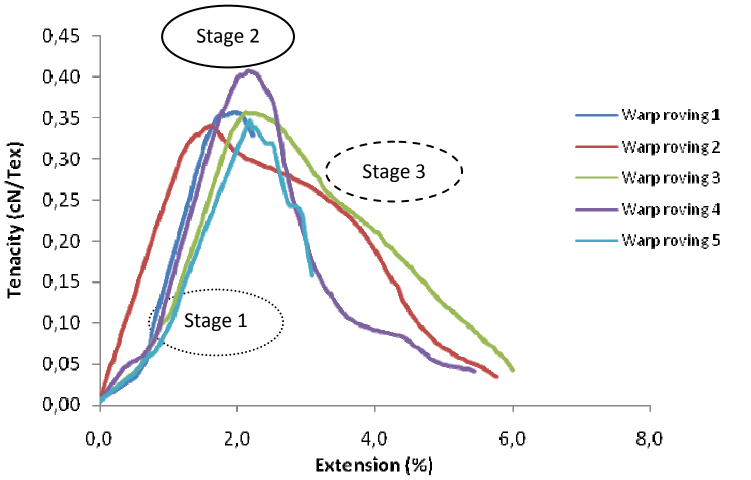


Figure 3.2 – Tenacity *vs* extension curve for warp rovings

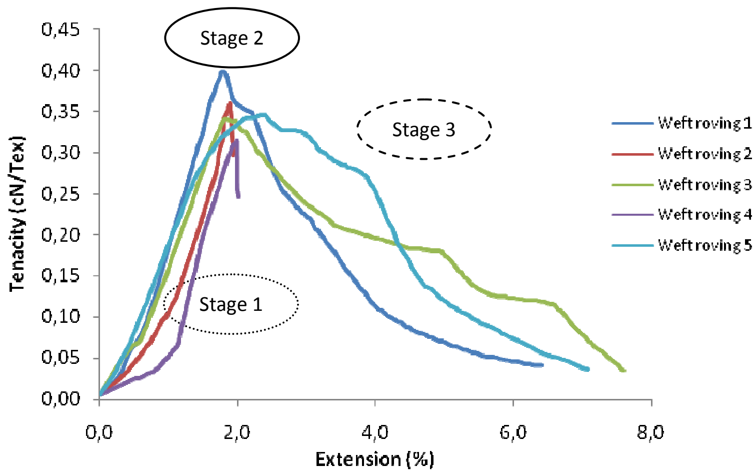


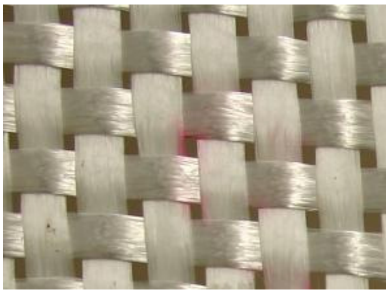
Figure 3.3 – Tenacity *vs* extension curve for weft rovings

3.3.2. Woven fabric structure

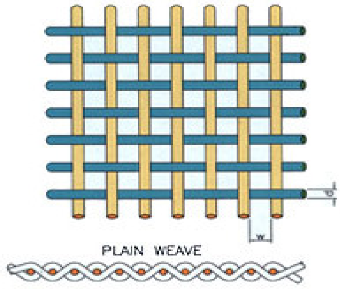
Usually, wovens fabrics structural characterization includes, weave structure, linear density, yarn density, thickness and mass per unit area and crimp. In this particular research work, crimp was neglected once the use of very large flat rovings and low interlacement density almost avoid this undesirable woven characteristic.

3.3.2.1. Weave structure

The woven fabric used within this work is made of E-glass fibre rovings in a plain weave structure (Figure 3.4), characterized by an interlacement of warp and weft where warp roving passes over and under alternately of each weft roving. This structure is symmetrical, with reasonable stability and good porosity. The present test was made according to the standard NP 4144: 1991 [78].



(a) plain weave fabric



(b) plain weave representation

Figure 3.4 – Woven fabric used in this work

This woven fabric was the base fibrous structure that was modified in order to produce the various directionally oriented fibrous structures (DOFS) used to reinforce the concrete slabs.

3.3.2.2. Linear density (tex)

Linear density (tex) is the relation between weight and length and could be calculated according to the following equation:

$$tex = \frac{p(g)}{l(km)} \quad \text{(Eq. 1)}$$

The tests were carried out according to the Portuguese standard NP 4105: 1990 [79] either for warp and weft rovings. However, once the standard is regarding to yarns, the test has been adapted for rovings. Thus, 20 warp and weft rovings, with 100cm, were weighted and the linear density for each one was calculated. The results are presented in the Table 3.3.

Table 3.3 – Warp and weft roving linear density

Direction	*Maximum (tex)*	*Minimum (tex)*	*Average (tex)*	*Standard deviation*	*Coefficient of variation (%)*
Warp roving	2277	1940	2130	86,48	4,05
Weft roving	2179	2090	2140	19,57	0,91

As it can be seen, warp and weft rovings present a similar linear density. The difference existing could be explained by filaments damage during the handling. For both, the coefficient of variation values is low.

3.3.2.3. Yarn structural density (yarns/cm)

According to the NP 1049-2: 1992 [80], yarn density gives the number of warp and weft yarns per width and length of 1cm of woven fabric. Numbers of rovings were counted in 50cm of length. The results for warp and weft directions are summarized in the following Table 3.4.

Table 3.4 – Warp and weft roving structural density

	Maximum (roving/cm)	*Minimum (roving/cm)*	*Average (roving/cm)*	*Standard deviation*	*Coefficient of variation (%)*
Warp roving/cm	2,5	2	2,5	0,25	11,42
Weft roving/cm	2	2	2	0	0

The results obtained for roving structural density are quite similar. However, warp direction presents an higher value of rovings per cm. The coefficient of variation value is low for warp roving density and zero for weft roving density which show a good representation of the values obtained.

3.3.2.4. Mass per unit area (g/m^2)

Mass per unit area has been performed according to EN NP 12127: 1999 [81] standard allowing the determination of the mass per unit area. It was calculated the mass per unit area of 15 x 30 cm (0,045 m^2). Five samples with that dimension were weighted and the mass per unit area was calculated. The results obtained are presented in Table 3.5. The mass per unit area was 836 g/m^2 with a low value of coefficient of variation.

Table 3.5 – Mass per unit area of the woven fabric

Maximum (g/m^2)	***Minimum (g/m^2)***	***Average (g/m^2)***	***Standard deviation***	***Coefficient of variation (%)***
837,556	824,889	836,074	10,52	1,26

3.3.2.5. Thickness (mm)

Thickness was measured according the EN NO ISO 5084: 1999 standard [82] using the Digital Gauge M034A equipment (Figure 3.5). Twenty samples were tested using 500 Pa of pressure. The results obtained are shown in Table 3.6.

Figure 3.5 – Determination of fabric thickness

Table 3.6 – Woven fabric thickness

Maximum (mm)	***Minimum (mm)***	***Average (mm)***	***Standard deviation***	***Coefficient of variation (%)***
1,50	1,11	1,29	0,10	7,89

The woven fabric thickness average is about 1,29 mm with a coefficient of variation lower than 10%.

3.3.2.6. Woven fabric mechanical properties

In order to assess the behaviour of the woven fabric used in this work, tensile tests were performed. Tensile tests were carried out on a *HOUNSFIELD H100 KS* tensile equipment according to the ASTM D638 [83] standard with the following test conditions:

- Speed: 25 mm/min
- Distance between jaws: 250 mm
- Extensometer
- Samples dimensions: 3 x 30 cm
- Pre-load: 10 N

Once the rovings slip from the jaws during the test, 5 cm of woven fabric ends were impregnated with resin in order to avoid rovings slippage. The use of extensometer was not very effective once during the testing rovings slipped from the extensometer.

Tests were carried out in warp and weft directions. Figure 3.6 shows samples used being tested in a tensile equipment.

(a) (b)

Figure 3.6 – (a) Samples (b) tensile test with the use of an extensometer

The results obtained in warp and weft directions for the woven fabric are summarized in Tables 3.7 and 3.8.

Table 3.7 – Mechanical properties of the woven fabric in warp direction

Samples	*E Modulus (MPa)*	*Max Tensile strength (MPa)*	*Max Load (N)*	*Extension at Max (%)*
1	84832	135,9	5258	0,4738
2	55759	164,0	6347	0,1700
3	44576	134,2	5193	0,2555
4	62566	140,5	5438	0,2025
AV	61933,25	143,65	5559	0,27545
SD	16972.02	13,83	535,46	0,14
CV	27,40	9,62	9,63	49,68

*AV = average; ** SD = standard deviation; ***CV = coefficient of friction

Table 3.8 – Mechanical properties of the woven fabric in weft direction

Samples	*E Modulus (MPa)*	*Max Tensile strength (MPa)*	*Max Load (N)*	*Extension at Max (%)*
1	33311	119,3	4615	0,275
2	58952	114,2	4420	0,175
3	36200	93,00	3600	0,306
4	27942	153,7	5947	0,285
AV	39101,25	120,05	4645,5	0,26
SD	13669,01	25,16	972,25	0,06
CV	34,96	20,96	20,94	22,36

*AV = average; ** SD = standard deviation; ***CV = coefficient of friction

As it can be seen from the results woven fabric in warp direction presents better performance when compared to the fabric weft direction. These results correspond on what was obtained for the rovings, where also warp rovings presented a better behaviour. CV values for fabric warp direction are lower with an exception on the maximum extension. However, it is noticed that there is, in both cases, an high variation between the samples tested. Once the woven fabric is made with rovings and these are composed by hundred of filaments, they are not able to bear the load at the same time. Some filaments have already been damaged due to the handling and processing, and others are more stretched than others. This implies that tensile strength of the fabric is not totally achieved.

The load *vs* extension curves obtained from the tests for warp and weft direction can be seen in Figure 3.7 and 3.8. At the initial stage of the curve both present a linear behaviour supporting loads up to the maximum force. However, in the fabric warp direction the samples in general do not present so higher deformation to the same applied load when compared to the weft direction which explains the higher Modulus. The tensile strength is achieved with higher results for warp direction. Finally, failure occurs with decrease of load bearing capacity.

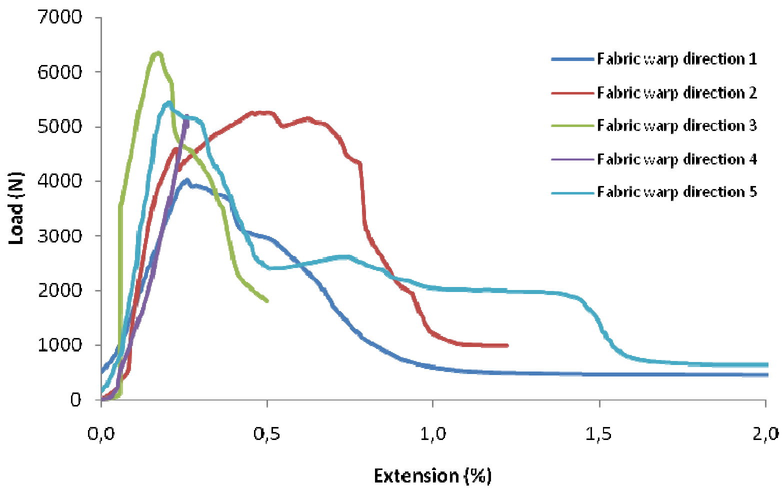


Figure 3.7 – Load *vs* extension curve of fabric warp direction

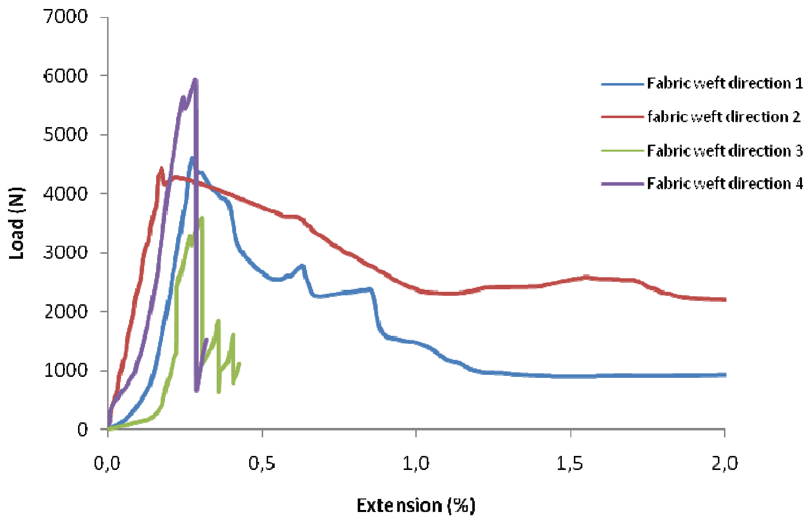


Figure 3.8 – Load *vs* extension curve of fabric weft direction

3.4. DEVELOPMENT OF DIRECTIONALLY ORIENTED FIBROUS STRUCTURES (DOFS)

3.4.1. DOFS design

DOFS woven fabrics were developed based on the basic plain woven structure characterized previously. In order to study the influence of roving linear density (tex) and structural density (roving/cm) several DOFS samples were developed.

The DOFS reinforcement consisted in a biaxial (2D) woven structure with $0/90^0$ (warp and weft direction) fibre orientation of E-glass fibre. The DOFS are characterized by an open structure with different number of rovings in each direction, as can be seen in Table 3.9 and in Figure 3.9, where fibre rovings are oriented in different loads directions, increasing the load bearing capacity. The mesh geometry is of paramount importance once either will influence the impregnation of the fibrous structure by the cementitious matrix as well as will avoid the retention of concrete coarse aggregates. Although the rovings are independent of each other, they are interlaced.

The development and production of directionally oriented fibrous structures (DOFS) had the main objective to understand the influence of DOFS geometrical and mechanical properties on the DOFS reinforced concrete elements. The study was regarding to the influence of the quantity, linear density (tex) and the distribution, structural density (roving/cm), of fibre rovings reinforcement in $0/90^0$ direction in order to achieve the optimized mechanical properties of the textile reinforced concrete (TRC) elements. Thus, the two variables analysed for DOFS were:

1. Roving linear density in two loading directions, longitudinal and transversal ($0/90^0$);
2. Roving structural density along the reinforced in two loading directions, longitudinal and transversal ($0/90^0$);

DOFS reinforcements are identified using four letters, ***DOFS***, meaning directionally orientated fibrous structures, followed by a number (1,2,...) corresponding to the structure used. Table 3.9 shows the characterization of the DOFS samples produced.

As the DOFS structures are to be used as concrete slabs reinforcement to be tested in bending, two directions of load applications are now defined: longitudinal and transversal. Transversal is defined as the rovings to be placed in parallel to the larger dimension of the slab and longitudinal defined as the rovings to be placed in parallel with the minor dimension. The DOFS structural density in longitudinal direction is presented for 15cm of area and in transversal direction for 30cm once corresponds to the slabs dimensions.

Table 3.9 – DOFS samples produced

Samples	***Longitudinal reinforcement***		***Transversal reinforcement***	
ID	*Roving linear density (tex)*	*Structural Density (rovings/15 cm)*	*Roving linear density (tex)*	*Structural Density (rovings/30 cm)*
$DOFS_1$	2130	4	2140	6
$DOFS_2$	2130	8	2140	6
$DOFS_3$	6460	4	2140	6
$DOFS_4$	8520	4	2140	6
$DOFS_5$	6460	4	2140	3
$DOFS_6$	2130	8	2140	3
$DOFS_7$	2130	16	2140	6
$DOFS_8$	6460	4	2140	12
$DOFS_9$	2130	8	2140	12
$DOFS_{10}$	8520	2	2140	6

The following examples show how the data in the Table 3.9 should be understood:

- $DOFS_1$ has 4 rovings in longitudinal direction having each one 2130 tex, and 6 rovings in transversal direction having each one 2140 Tex; regarding to rovings density the fibrous structure presents 4 reinforcements per 15cm in longitudinal direction while in the transversal direction has 6 per 30cm.
- $DOFS_{10}$ in terms of linear density presents 2 rovings having each one 8520 tex in the longitudinal direction while in the transversal direction presents 6 rovings having each one 2140 tex; regarding to density this structure presents 2 longitudinal reinforcements with 4 rovings each one and 6 reinforcements with one roving each in the transversal direction.

The following Figure 3.9 shows schematically the design of the ten DOFS structures developed.

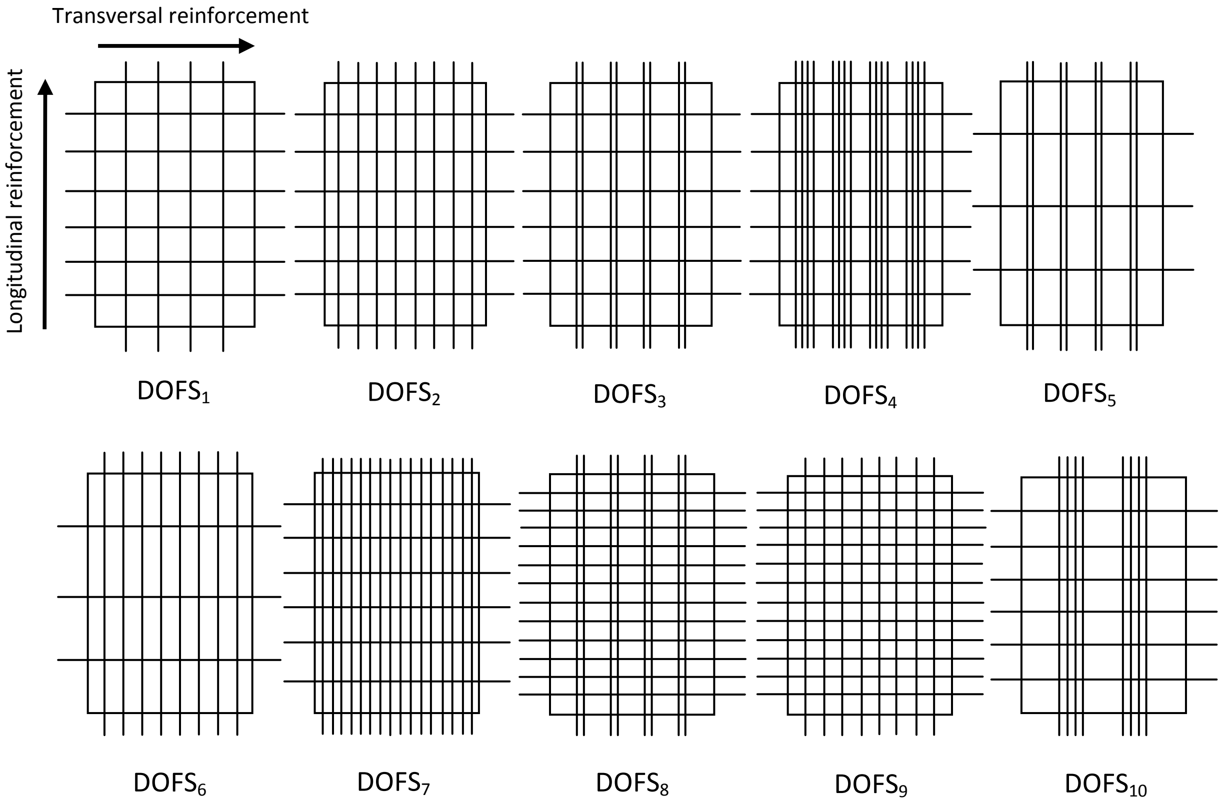


Figure 3.9 – DOFS structures schematic representation

Considering the ten DOFS, some relations can be established in order to evaluate the influence of quantity (roving linear density) and distribution (roving structural density) in longitudinal and transversal direction on the DOFS reinforced concrete slabs mechanical properties, namely:

- Group 1 - DOFS 1, 2, and 7, evaluation of the influence of density increase in longitudinal direction and its distribution along the reinforced element, keeping the transversal direction constant (Figure 3.10);

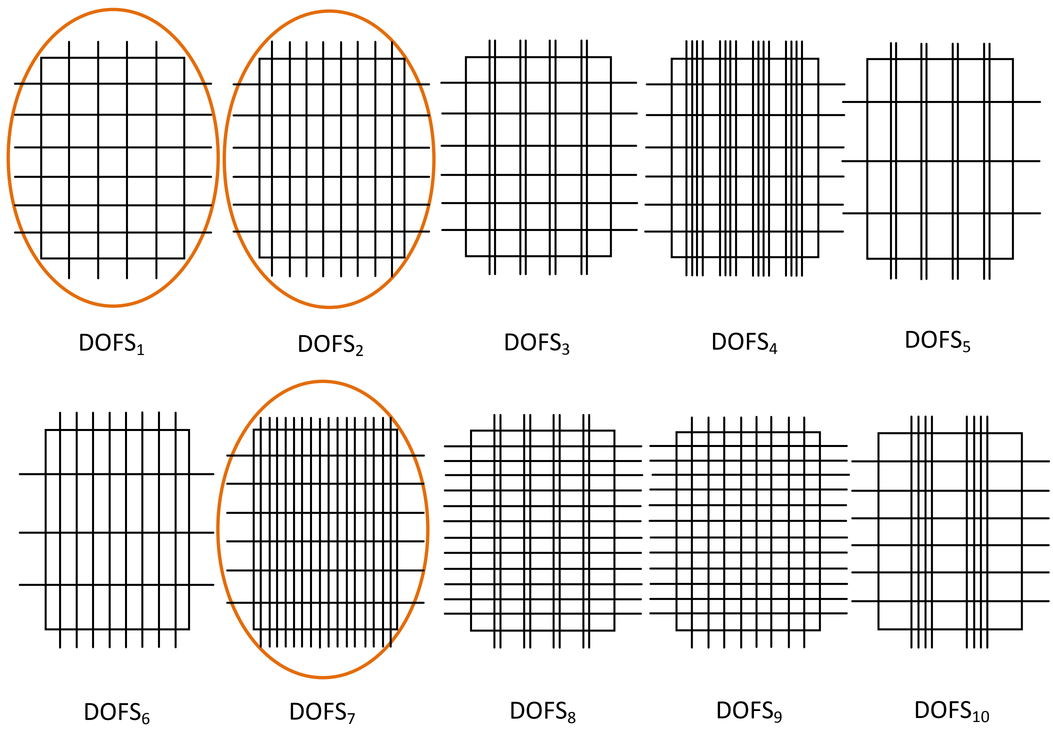


Figure 3.10 – Relation established in Group 1

- Group 2 - DOFS 1, 3 and 4, evaluation of the influence of the quantity increase (linear density) in longitudinal reinforcement along the reinforced element keeping the transversal direction constant (Figure 3.11);

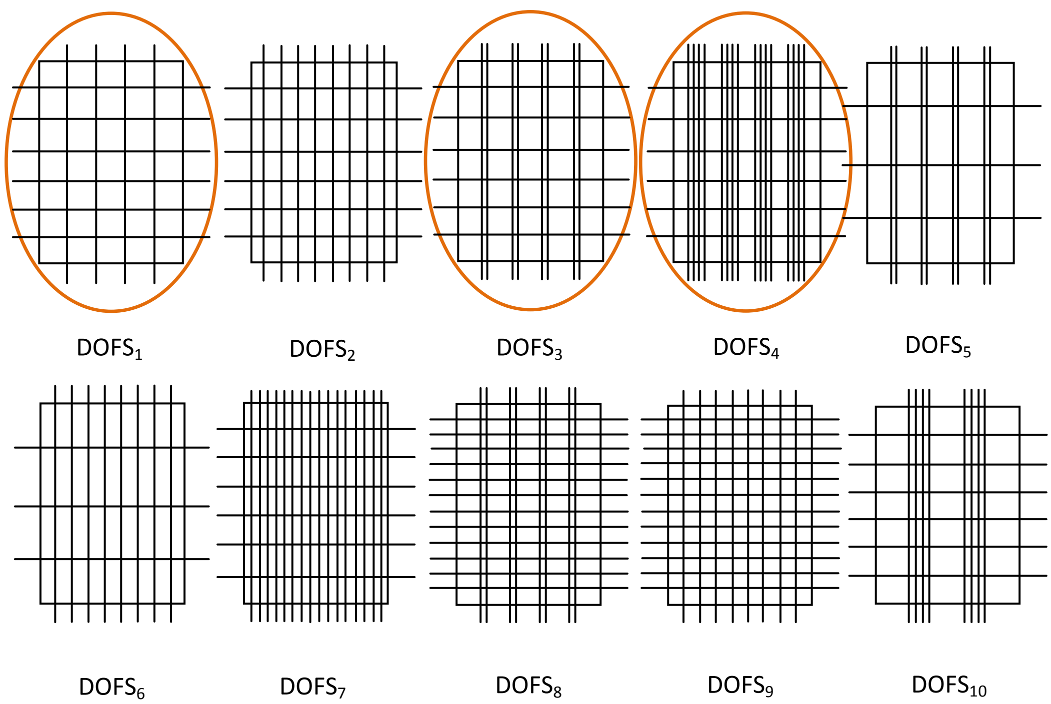


Figure 3.11 – Relation established in Group 2

- Group 3 - DOFS 2, 3 and 10, evaluation of the influence of rovings distribution along the reinforced element in longitudinal direction, keeping the transversal direction constant (Figure 3.12);

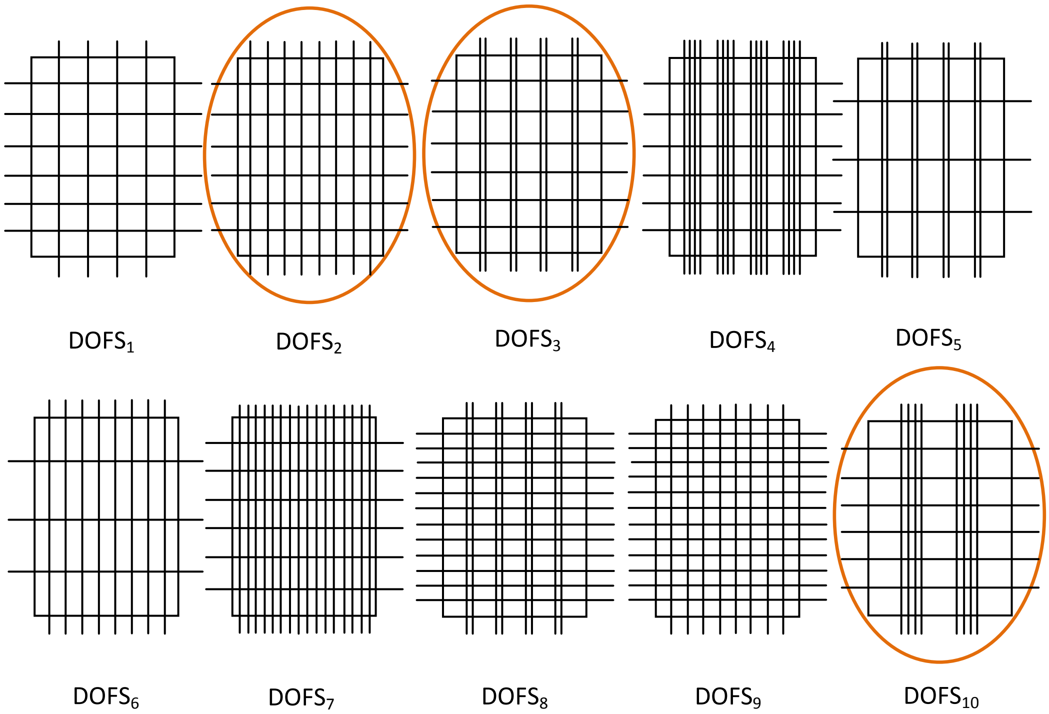


Figure 3.12 – Relation established in Group 3

- Group 4 - DOFS 5, 3 and 8, evaluation of the influence of the structural density of rovings increase and their distribution along the reinforced element in transversal reinforcement, keeping the longitudinal reinforcement (Figure 3.13)

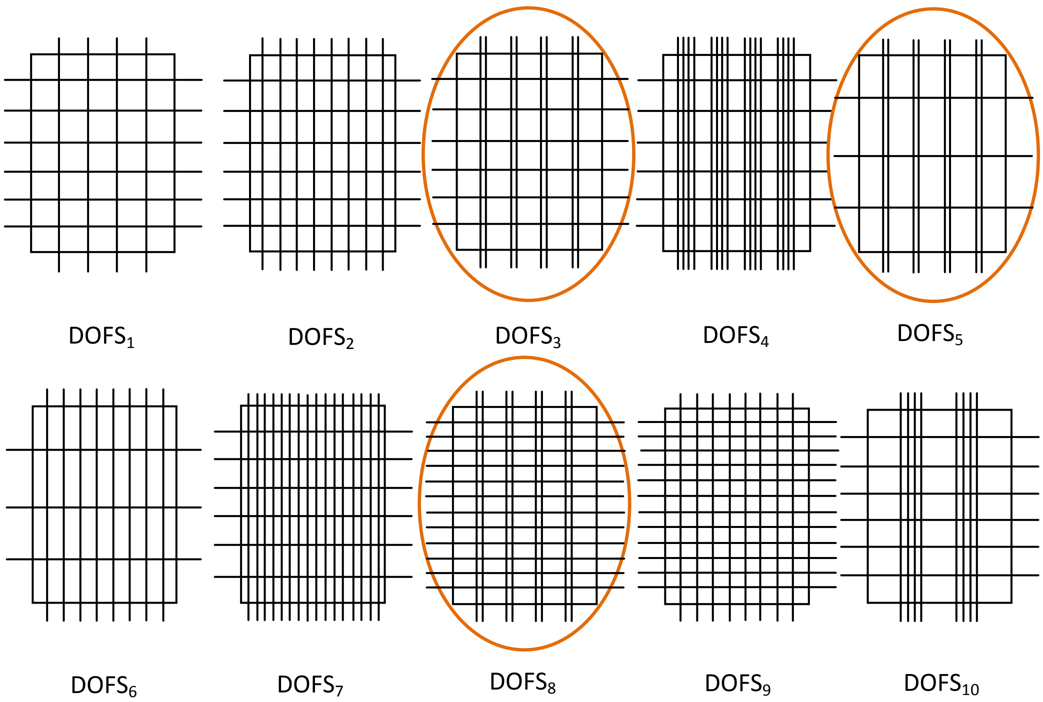


Figure 3.13 – Relation established in Group 4

- Group 5 - DOFS 6, 2 and 9, evaluation of the influence of the structural density of rovings increase and their distribution along the reinforced element in transversal reinforcement, maintaining the longitudinal (Figure 3.14).

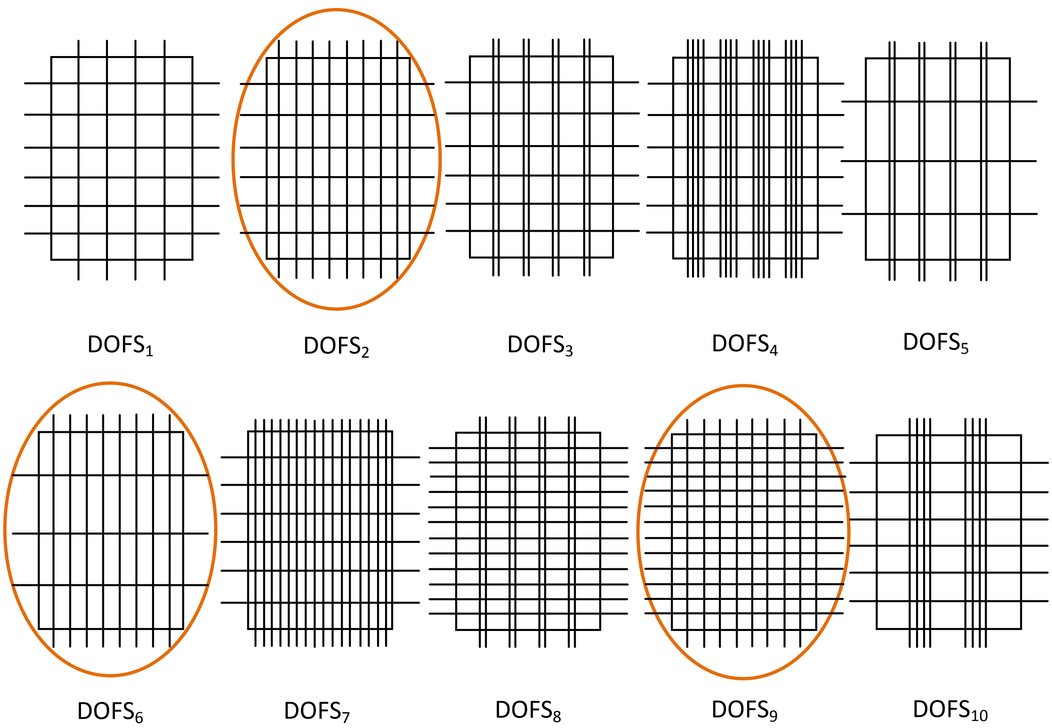


Figure 3.14 – Relation established in Group 5

Other relationships can be identified when considering the transversal reinforcement as a constant parameter, but with minor relevance for the study, such as:

- DOFS 4 and 7 evaluate the influence of the roving structural density increase of longitudinal reinforcement and their distribution along the reinforced element;
- DOFS 4 and 10, evaluate the influence of the roving structural density decrease of transversal reinforcement and their distribution along the reinforced element.

3.4.2. DOFS production

At the beginning of the work the construction of the DOFS were made manually without any type of device help. However, due to the high structure flexibility and, therefore, difficulty to handle and maintain the structure straight, it was necessary to apply resin in the interlacing points of warp and weft rovings. Moreover during the concrete slabs production, the structure displacement and unstraight placement inside the concrete (Figure 3.15) were problems to take into consideration.

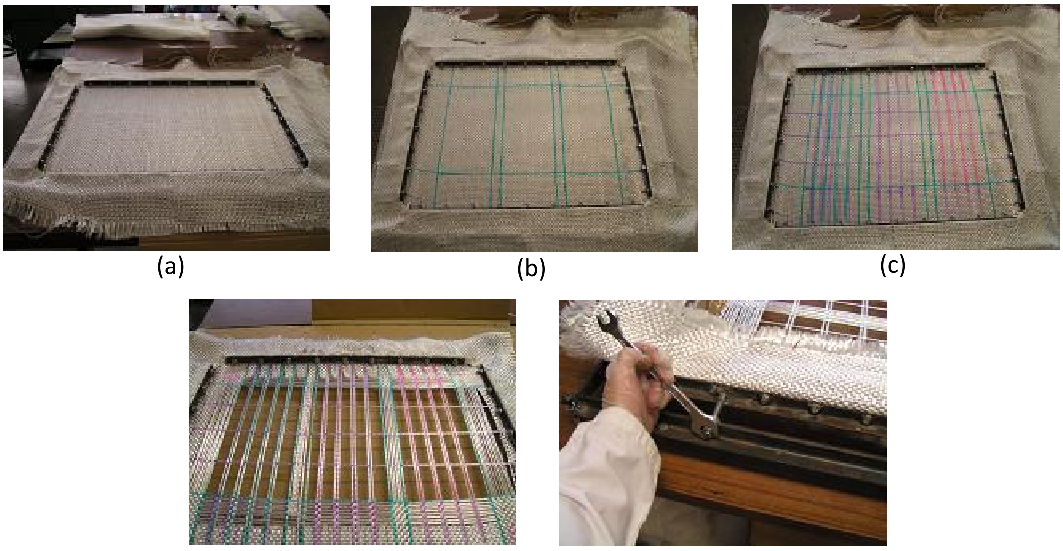
Figure 3.15 – Production and placing of fibrous structure in the concrete

The main conclusions of the preliminary slabs and fibrous structures production, led to the development of a new device able to hold the structure straighten during their production, as well as during the concrete casting process, being relatively easy to handle. Thus, a rigid steel pre-stressing frame was developed in order to solve the above mentioned problems (Figure 3.16). The frame was produced in steel and has four sides. In each interior side a steel bar is tighten up with nuts, in order to hold the fibrous structure. Besides, the steel bars, the frame possess also screw nuts in the exterior side to stretch the fibrous structure.

Figure 3.16 – Rigid steel pre-stressing frame

Considering the structures design in the previously section and having the rigid steel pre-stressing frame, the production of each structure was relatively easy. Thus, the production technique of DOFS structure consisted in the following steps (Figure 3.17):

a) The fabric is placed in the rigid steel pre-stressing frame and tighten up;
b) The dimensions of the slabs are marked in the fabric;
c) The DOFS structure is designed on the fabric;
d) DOFS structure is produced cutting the unnecessary rovings in warp and weft direction and finally the all structure is stretched.



(a) (b) (c)

(d)

Figure 3.17 – DOFS production technique

The whole set of directionally oriented fibrous structures were produced using this production technique developed for this purpose.

CHAPTER IV

APPLICATION OF DIRECTIONALLY ORIENTED FIBROUS STRUCTURES IN CONCRETE SLABS REINFORCEMENT

4.1. INTRODUCTION

Although it is an excellent material in terms of mouldability and compression resistance, concrete presents a weak capability of tensile strength, representing a serious limitation to its use without any type of reinforcement. As a consequence, concrete element tends to crack revealing its fragile nature and constituting its main weak point. The tendency for cracking causes a reduction on concrete serviceability once allows the penetration of chemical agents able attack concrete and the armours/reinforcement.

Concrete elements need to be reinforced due to a fundamental lack of adequate tensile strength. One of the most largely used reinforcement material for concrete elements is steel. Currently, the most widely accepted form of reinforcement is welded-wire mesh (WWM), a mesh of steel rods that is placed in concrete. Due to the use of steel rods whose tensile strength is several times higher than concrete the load capacity of the concrete elements subjects to bending is considerably increased. The steel-concrete is in combination, a building material whose application field is almost unlimited. The way how steel-concrete works is guaranteed by the combination of some physic-mechanical properties inherent to both materials, including:

- concrete adheres strongly to steel rods ensuring the simultaneous deformation of both materials when subject to loads;
- a dense, compact concrete having the necessary proportion of cement, protects steel from corrosion and fire;

- both materials present similar coefficient of thermal expansion, and so temperature variations up to 100^{o}C do not cause tensions as well as steel slipping in concrete.

However, due to steel corrosion, fatigue and other degradation agents, failure of steel reinforced concrete structures is an unavoidable consequence. Therefore, steel as concrete reinforcement material presents three major drawbacks namely, corrosion, limited service life and high maintenance costs of the concrete structure. Thus, the development of alternative materials to steel for concrete reinforcement has been a priority.

In civil construction field, and particularly in what concerns to the use of concrete as matrix, in the last years appeared several composites reinforced by natural or synthetic fibres. The purpose of these reinforcements in concrete is to increase the performance tensile, for instance. The objective is to ensure continuity through a net in the cementitious matrix, in order to establish loads transference through it, even if matrix continuity is interrupted by micro-cracks. Also, fibres contribute for the reduction of crack phenomenon [72, 74, 75, 91].

The composite performance is a function of the fibres volume and their physical and mechanical properties, as well as, the matrix and the adhesion between both. Generally it is necessary to assure the workability of concrete once the addition of fibres modifies this property. Once this parameter is controlled, the composite performance, improves with the increase of fibres percentage and their quality, this leads to a raise in the energy absorption capacity of the material side by side with the ductility increase. The most perfect mechanism consists in the fibres slippage in the contact interface of the cementitious matrix, favouring the plasticisation phenomenon instead of rupture [72].

The adhesion capacity between fibre and matrix usually does not exceed 4MPa but could be lower when considering polymeric fibres. The adhesion is also influenced by the weather and environmental conditions that could change the interphase matrix-fibre. Normally, the fibre extension at break is 10 times higher than the matrix as it can be seen in Table 4.1. Taking into consideration that matrix cracks before fibre tensile resistance is achieved, is obvious the fibre efficiency on the cracked matrix behaviour [72].

Table 4.1 – Fibre and cementitious matrices characteristics [72]

Matrix or fibre	***Density***	***Thickness (μm)***	***Length (mm)***	***Modulus Elasticity (GPa)***	***Tensile strength (MPa)***	***Extension at break (%)***	***Volume in composite (%)***
Mortar	1,8-2	300-5000	-	10-30	1-10	0,01-0,05	85-97
Concrete	1,8-2,4	10000-20000	-	20-40	1-4	0,01-0,02	97-99,5
Polyamides	1,45	10-15	5-continuous	70-130	2900	2-4	1-5
Asbestos	2,55	0,02-30	5-40	164	200-1800	2-3	5-15
Carbon	1,16-1,95	7.18	3-continuous	30-390	600-2700	5-204	3-5
Glass	2,56	12,5	10-50	70	600-2500	3,6	3-7
HM Polyethylene	0,96	20-50	continuous	10-30	>400	>4	5-10
Polypropylene	0,91	20-100	5-20	4	-	-	0,1-0,2
Steel	7,86	100-600	10-60	200	700-20000	03-Mai	0,5-2

It is important to refer that mortar and concrete matrices are different namely in particles dimensions. In concrete the maximum dimension of these particles are extremely important once they conditioned the fibre distribution and its quantity. The medium size particle on mortar is lower than 5mm while in concrete should be between 10-30mm. To use fibre as concrete reinforcement, the particles should not exceed 10mm otherwise dispersion of the fibres in the concrete matrix will be difficult.

The concrete behaviour to several solicitations like, tensile, compression and shear is quite different as it is influenced, not only, by the relation of its components quantities mainly by the relation water/cement once it affects the modulus of elasticity, but also by the inequality of particles distribution and the porous-empties inside the concrete. Therefore matrix properties could vary a lot in each concrete mixture.

Fibrous materials determinate an unique crack behaviour in concrete matrix. This one could be divided in crack propagation immobilization or by the load capacity conservation through the fibre. First case occurs from the porous area weakness in the interface between the fibre and the matrix, causing fibre displacement. In the second case, with the crack already developed and propagated beyond the fibre, still reflects in an addition on the necessary energy when a new surface around the fibre is developed, with the disconnecting of the fibre from the matrix, as well as a locking up force caused by the fibre.

When the fibre is intersected by the crack and its ends are anchored, it continuous to transfer load between the two surfaces distant from the crack conserving the resistance capacity in that region of the material, i.e., crack does not affect the fibre surrounding. This situation remains till two situations are verified: the fibre resistance capacity to a tensile effort is broken-down and the fibre breaks, and the adhesion capacity between the fibre and the matrix is broken-down and then the fibre starts to slip as the crack width is increasing.

Multiple cracking phenomenon occurs in fragile materials of cementitious matrix when an efficient reinforcement system is used transforming it in a pseudo-ductile material. Fragile materials can be transformed, in a certain manner, in plastic materials when some reinforcing elements are incorporated either through fibres or rods. When fibres are used as reinforcement, the aim is to reduce the cracking and, at the same time improve the energy absorption on the process load/extension that material will be subject [11, 71, 72].

4.2. EXPERIMENTAL PLAN

The experimental plan has been established in order to understand the influence of roving linear density (tex) and reinforcement structural density (roving/cm) on the bending mechanical behaviour of lightweight concrete slabs reinforced by DOFS.

A set of experiences were planned to evaluate the bending behaviour of the DOFS reinforced lightweight concrete slabs.

Ten different DOFS structures, according to the description given in chapter III, were used in order to reinforce concrete slabs. Plain concrete slabs and steel reinforced concrete slabs were also produced, in order to perform a behaviour comparison analysis.

Pull-out tests were performed on rovings used as concrete reinforcement in order to analyse the interface strength provided by both materials.

4.3. DOFS REINFORCED CONCRETE SLABS PRODUCTION

4.3.1. Mould

A mould was developed to produce the concrete slabs, giving the final geometry required.

The first mould made of wood, was produced with 40x78x5cm given the possibility to produce three samples at the same time with 26x40x5 cm. This mould was rejected once it was extremely difficult to remove the slabs due to their large dimensions.

A second mould made of steel consisted in an unique structure divided in two parts: the lower one with six divisions separated by a steel bar, with the dimensions (15x30x5 cm) desired for the concrete slabs, and a superior which was placed above the stretched fibrous structure and then attached to the lower by screws. With this solution it was expected to solve the problem related to concrete slabs remotion. Besides, six slabs were able to be produce simultaneously. Figure 4.1 shows the steel mould with the fibrous structure stretched.

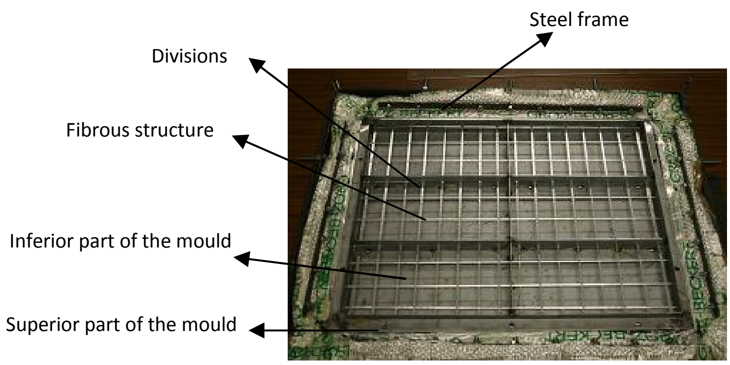


Figure 4.1 – Steel mould with six divisions

Preliminary slabs were produced to assess the effectiveness of the frame and mould. The steel pre-stressing frame worked perfectly but the some does not happen to the mould. The main problem of the mould consisted in the slabs removal. Even with the help of special oil, slabs obtained were to damage to be tested as it can be seen in Figure 4.2.

Figure 4.2 – Damaged concrete slab after demoulding

Therefore a new mould (Figure 4.3) was designed in order to overcome the problem of the previously ones. The solution was to build a mould easy to use, reusable and allowing the easy demoulding of the concrete slabs. A mould made of plywood was produced. This new mould was constituted by two parts also: the inferior part divided into three sections with 15x30x4 cm dimensions separated by a wood bar of 2cm and a superior part to place above the stretched fibrous structure, attached to the inferior part with screws. However, the result was not satisfactory, when the slabs needed to be demoulded the 2 cm of wood bar made the demoulding process very difficult.

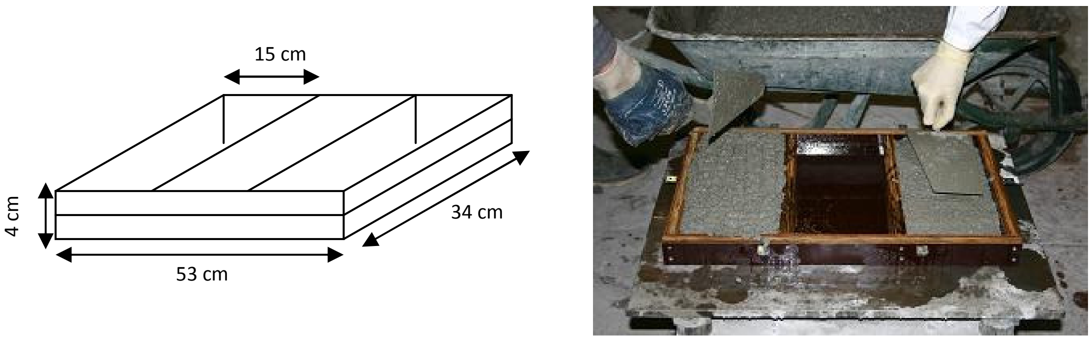


Figure 4.3 – Third mould

New moulds were developed based on the previously one but without the 2cm wood bar used to divide the slabs, being completely dismountable. The results with this new mould were very good once it allowed an easy production of the slabs as well as demoulding. After the curing period concrete slabs were cut in pieces of 15x30 cm using a saw. Figure 4.4 presents the new mould developed.

Figure 4.4 – The final mould

4.3.2. Self-compacting concrete (SCC)

Conventional concrete was used to produce the concrete slabs at the beginning of the project. However, during their production some problems were found namely, difficulty to fill completely the mould and to keep the DOFS structure without damages and displacements once during the concrete casting was necessary to spread the concrete over the fibrous structure. In order to overcome the problems encountered, a self-compacting concrete (SCC) was selected and used to evaluate the mechanical performance of glass fibre DOFS when reinforcing concrete slabs.

This type of concrete is considered an *High Performance Concrete* with excellent deformability in the fresh state and high resistance to segregation, and can be placed and compacted under self weight without applying vibration. SCC presents higher tensile strength than ordinary concrete due to its microstructure, presenting higher content of ultra fine materials leading to a denser cement matrix. Moreover, self-compacting concrete does not require vibration for placing and compaction, being able to flow under its own weight, fills completely the formwork/mould and restricted sections and hard to reach areas achieving full compaction, reduces and avoid costly labour operations and presents the same or higher engineering properties than the traditional vibrated concrete. Other benefits in use SCC are:

- in the presence of dense reinforcement keeps the homogeneity without the need for any additional compaction;
- enhances consolidation around reinforcement and bond reinforcement;
- improves and allows more uniform architectural surface;
- opportunities to create structural and architectural shapes with surfaces finishes not achieved with conventional concrete.

In SCC, fibrous materials can be used also to improve its stability once they help to prevent settlement and cracking due to plastic shrinkage of the concrete.

The composition of SCC is very similar to that of conventional concrete once the basic compounds are the same. The main difference is found in the higher proportion of ultra fine materials and in the introduction of chemical admixtures namely a superplasticizer (viscosity-modifying agent) in order to increase the concrete workability as well as, a filler to improve particle packing and reduce the amount of cement in concrete without loss of strength [73,74,75,76].

The SCC composition used for a set of six slabs and for a volume of 15 L, is given in Table 4.2. A cement type I 42,5 R was used and a calcareous filler was added as well as a 3rd generation superplasticizer.

Table 4.2 – Self-compacting concrete composition

Components	***Quantity***
CEM I 42,5 R	289,33 kg/m^3
Calcareous Filler Micro 100 A	376 kg/m^3
Water	161,27 l/m^3
Superplasticizer SikaViscocrete 3006	5,07 l/m^3
Sand	738,2 kg/m^3
Granite aggregates 4/10*	756 kg/m^3

* at least 95% of the aggregate particles has dimension higher than 4mm; at least 90% of the aggregate particles has dimension lower than 10mm

4.3.3. Pull-out tests

The reinforcement slip inside concrete is opposed by the adhesion existing between them. Usually studies are made in order to determine the adhesion limit, pulling out the rods from the concrete either by tensile or compression. Nevertheless, in last year's the same studies are being performed using bending tests in reinforced concrete elements. These studies have been showing that adhesion between steel and concrete can vary significantly depending mainly from three parameters [11]:

- adhesion provided by the adhesion properties from cement paste;
- friction forces by the union of steel and concrete due to retraction of this one;
- concrete strength to shear loads due to rods roughness and other surfaces irregularities around the moulded concrete.

However, when reinforcements are not steel but fibrous materials, the bonding/adhesion mechanism is completely different. According to *Peled* and Bentur [45] it has been reported by several researchers that there is a relationship between the modulus elasticity of the fibre on the bond fibre-concrete. The some research work refers that, the higher is the modulus elasticity the better is the bond strength. Low modulus fibres such as, polypropylene and polyethylene develop low bond with cementitious matrix, while fibres that present high modulus like glass and carbon fibre, provide strong bond. This could be explained by the fact that fibres with high modulus present higher clamping stresses which develop around the fibres due to matrix autogenous shrinkage [45].

The basic mechanism regarding bond between fibrous materials and concrete is not yet understood in detail so far. Although fibrous materials and concrete will built up a good composite material, its success will depend mainly on bond strength. However, the bond properties between fibrous materials and concrete may differ from those between conventional steel rods and concrete. The shape of textile roving cross section embedded in concrete can vary, while the shape and the area of the cross section of a steel rod is well defined and can be exactly measured. Moreover each single filament among the thousands of filaments of a textile roving cannot be fully infiltrated with cement due to voids among the inner filaments. Because of this it is difficult to characterize the bond stress *versus* slip relationship of fibrous materials reinforcement.

Rovings composed by multifilaments are considered as one but it is necessary to distinguish outer and inner filaments. This distinction needs to be considered once the outer filaments are bonded in the cementitious matrix while the inner filaments are not or, depending on the penetration of cement past into the roving bonded only to a smaller extent. This makes the inner filaments slip when there is a differential force like at a crack or an anchorage. The slip is more accentuated when the friction between filaments is small and when the fluid does not penetrate into the interior of the roving [77]. While the outer filaments which are embedded in the cementitious matrix, transfers most of the load, the inner filaments of the fibrous material contribute only minor on the load transmission probably by friction.

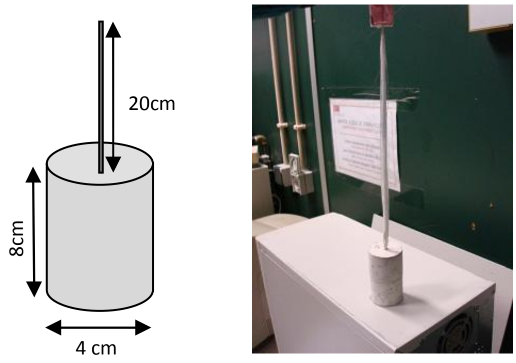
During some of the bending tests performed DOFS seems to slip in the concrete. Once the system of the composite it was composed only by the concrete as matrix and the fibre as reinforcement, without any type of resin, the adhesion between both is much different from those fibres which are coated/impregnated by resins. Thus, it was decided to evaluate the fibre adhesion/bonding behaviour to the cementitious matrix.

4.3.3.1. Experimental work

A. Samples preparation

In order to study the slipping effect of fibres rovings in cementitious matrix, several samples of concrete with fibre rovings in the centre were produced.

Samples were produced with the same type of concrete as slabs, self-compacting concrete, using cylinder moulds with 8cm in height and 4cm of diameter (Figure 4.5).



(a) (b)

Figure 4.5 – (a) Sample dimensions (b) sample

Different number of rovings where placed into the mould centre. The criteria used to select the number of rovings where the number also used in the DOFS structures. Thus, were produced samples with one, two and four rovings placed in the middle of concrete cylinders as shown in Table 4.3.

Table 4.3 – Number of rovings used in the samples

Samples	***Rovings number***	***Linear density (tex)***
A	1	2130
B	2	4260
C	4	8520

Rovings needed to be fixed in the bottom of the mould. This procedure was necessary once during the mould filling with concrete, fibres rovings moved from the centre.

Resin was applied in the ends of rovings in order to avoid fibre slippage in the jaws of the equipment. Figure 4.6 presents cylinders samples with rovings ends with resin.

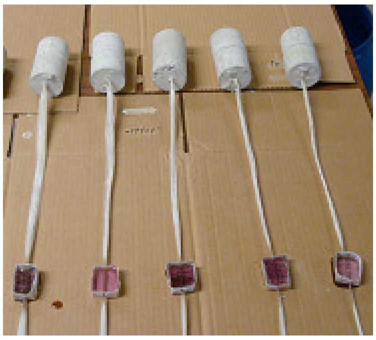


Figure 4.6 – Samples with fibre roving ends with resin

Table 4.4 shows the concrete composition used to produce cylinder SCC samples.

Table 4.4 – Self-compacting concrete composition

Components	***Quantity***
CEM I 42,5 R	1,16 kg/m^3
Calcareous Filler Micro 100 A	1,50 kg/m^3
Water	0,02 l/m^3
Superplasticizer SikaViscocrete 3006	5,07 l/m^3
Sand	2,94 kg/m^3
Granite aggregates 4/10	3,02 kg/m^3

The SCC cylinder samples were demoulded after 24 hours and placed in a controlled environment (20^0C and 65% RH) during 14 days for curing till testing.

B. Testing

Once it was not found a specific standard to perform this test for this type of material, an internal proceeding was used. The tests were carried out using a tensile equipment *LLOYD Instrument LR30K.* The procedure testing was as follows:

- fix samples with a special glue to a steel component from the equipment (Figure 4.7a);
- hold samples in the jaw equipment lining up the sample longitudinal axis with the mechanical axis of the equipment; samples were very well tighten up in order to avoid any slippage (Figure 4.7b);

- regulation of tensile velocity for 0,2mm/seg and registration of elongations and correspondent loads.

(a) (b)

Figure 4.7 – Pull-out tests

C. Results

The average results obtained from the pull-out tests are summarized in the Table 4.5. As expected sample C, with 4 rovings in the middle, present the highest value for maximum load while the sample A, with a single roving, presents the worst result. In all samples the value elongation corresponding to the maximum load are very similar. Comparing these results to that of roving results obtained in the beginning of the work, one can see that the values are lower than it was expected. This could be explained due to the rovings anchorage to the concrete and due to the fibre damage during the samples preparation.

Table 4.5 – Maximum values of load and respective elongation

Sample	***Max Load (N)***	***Max Elongation (mm)***	***Max Extension (%)***
A – 1 roving	393,68	4,89	2,45
B – 2 rovings	526,43	4,51	2,26
C – 4 rovings	663,75	4,95	2,48

During testing, no slip has been observed before fibre roving rupture. Figure ??? shows the load *vs* elongation curve for each sample tested. The curve is characterized by three distinct stages: the first stage corresponds to load carrying by the fibre roving till the rupture; the second stage corresponds to fibre roving rupture load; and the third stage corresponds to an accentuated decrease on load bearing capacity. The values obtained for Maximum Load corresponds to the filaments rupture. Moreover, analysing Figure 4.8, no stairs-like behaviour at the linear part of the curve is observed. In this way it is possible to conclude that no slip effect has been observed occurred in the interphase concrete/filament. It is also to considerer that, according to the literature, glass fibre, which as an high modulus of elasticity, usually presents a good bond between fibre and concrete matrix.

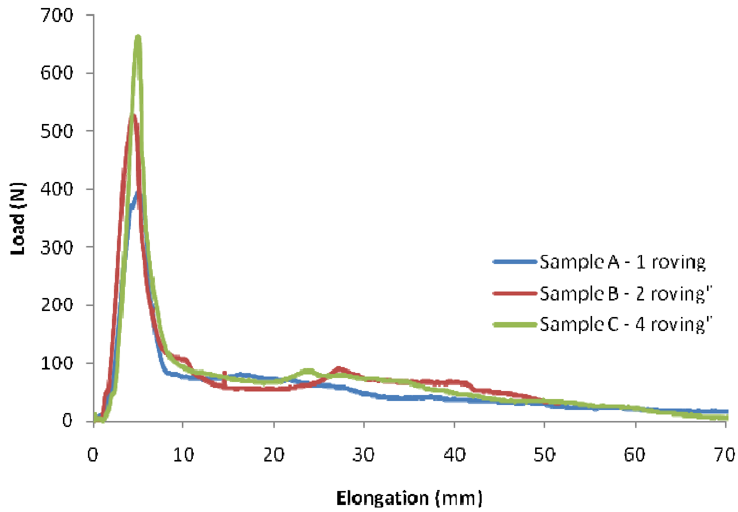


Figure 4.8 – Curve of load *vs* elongation of pull-out samples

However, an accurate and deep study regarding to adhesion of fibre-concrete needs to be performed including the improvement on samples production, as well as, test procedure.

4.3.4. DOFS reinforced concrete slabs – samples production

The DOFS were produced as described in the previous section, using a pre-stressing frame, in order to achieve a completely stretched fibrous structure in transversal and longitudinal directions. Figure 4.9 presents a DOFS structure in the pre-stressing frame.

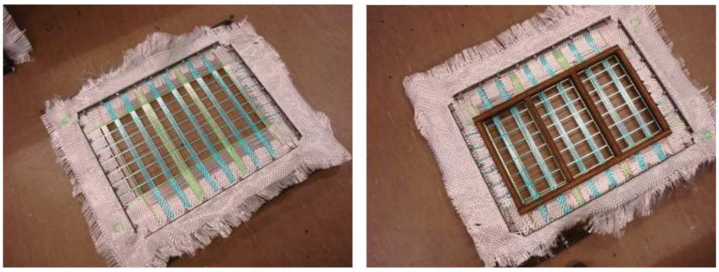


Figure 4.9 – DOFS structure in pre-stressing frame

A demoulding oil was applied to the mould surface in order to allow an easy removal. Afterwards, the self-compacting concrete was produced according to the mentioned composition (Figure 4.10). Aggregates where weight and placed in a local with no humidity variation one day before the casting to control water contents.

Figure 4.10 – Self-compacting concrete production in a concrete mixer

A SCC layer of 1cm height was laid inside the mould. The stretched DOFS was then placed above the mould filled with self-compacting concrete (Figure 4.11a). Finally, another layer of SCC, 3cm height, was laid on the top of DOFS (Figure 4.11b).

(a) (b)

Figure 4.11 – DOFS reinforced concrete slabs production

The SCC samples (Figure 4.12) were demoulded after 24 hours and placed in a controlled environment (20^0C and 65% RH) during 28 days for curing till testing. Curing is important for all concrete specimens but especially for the elements top-surface made with SCC. This can dry quickly because of the increased quantity of paste, the low water/fines ratio and the lack of bleed water at the surface. Initial curing should therefore commence as soon as practicable after placing and finishing, in order to minimise the risk of surface crusting and shrinkage cracks caused by early age moisture evaporation.

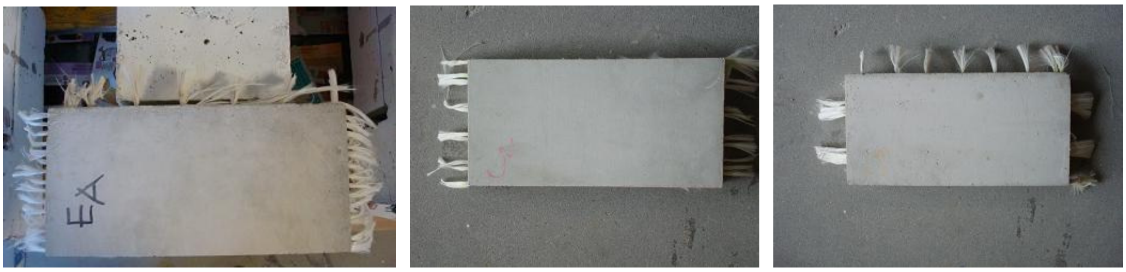


Figure 4.12 – Examples of DOFS reinforced concrete slabs produced

Three samples were produced for each type of DOFS reinforced concrete slabs. Thirty samples of DOFS reinforced concrete slabs were produced with the 10 different DOFS. Besides, one set of plain concrete slabs and steel reinforced concrete slabs were also produced in order to compare the steel and DOFS mechanical behaviour when reinforcing concrete. The steel used was a soft steel mesh and the configuration (Figure 4.13) was the same as the first DOFS structure.

Figure 4.13 – Steel structure

4.4. REINFORCEMENT VOLUME FRACTION

Considering the density of glass fibre and steel, volume fraction of each reinforcement used was calculated for each slab. The equations used for that calculation were:

$$\rho = \frac{m(kg)}{V(m^3)} \qquad \text{(Eq.2)}$$

$$V(\%)_{re\inf orcement} = \frac{V_{re\inf orcement}}{V_{total}} * 100 \qquad \text{(Eq.3)}$$

$$V_{total} = V_{re\inf orcement} + V_{concrete} \qquad \text{(Eq.4)}$$

- ρ = density (g/m^3)
- m = reinforcement mass (kg)
- V = volume of fibre roving or steel (m^3)
- $V_{reinforcement}$ = volume of the reinforcement (m^3)
- V_{total} = volume of the reinforcement and the concrete (m^3)
- Glass fibre density = 2,56 g/cm^3; Steel density = 7,86 g/cm^3
- Slabs dimension = 15 x 30 x 4 cm

The results regarding to the percentage of steel and glass fibres in each concrete slab can be seen in Table 4.6 and 4.7 respectively. The results are divided by the relations establish in the previously chapter. Each relation corresponds to the previously established groups.

Table 4.6 – Percentage of steel reinforcement in each slab

Id samples	*Steel (% volume)*	*Longitudinal steel (% volume)*	*Transversal steel (% volume)*
SCC_{steel}	0,62	0,352	0,265

Table 4.7 – Percentage of glass reinforcement in each slab

Group	***Id samples***	***Glass fibre (% volume)***	***Longitudinal fibres (% volume)***	***Transversal fibres (% volume)***
1	SCC $DOFS_1$	0,08	0,046	0,035
	SCC $DOFS_2$	0,13	0,093	0,035
	SCC $DOFS_7$	0,22	0,184	0,035
2	SCC $DOFS_1$	0,08	0,046	0,035
	SCC $DOFS_3$	0,13	0,093	0,035
	SCC $DOFS_4$	0,22	0,184	0,035
3	SCC $DOFS_2$	0,13	0,093	0,035
	SCC $DOFS_3$	0,13	0,093	0,035
	SCC $DOFS_{10}$	0,13	0,093	0,035
4	SCC $DOFS_3$	0,13	0,093	0,035
	SCC $DOFS_5$	0,11	0,093	0,017
	SCC $DOFS_8$	0,16	0,093	0,070
5	SCC $DOFS_2$	0,13	0,093	0,035
	SCC $DOFS_6$	0,11	0,093	0,017
	SCC $DOFS_9$	0,16	0,093	0,070

Analysing the Tables 4.6 and 4.7 it is possible to observe that steel, in terms of % value is four times higher that of glass fibre reinforcement either in longitudinal and transversal directions. So it is expected that slabs reinforced with steel will present a different behaviour than those reinforced with E-glass fibres.

There is not a worldwide consensus regarding to the ideal value for the fibre volume fraction in concrete. Fibre volume (%) varies. The effect of reinforcement is proportional to the volume and efficiency of the fibres. Once fibrous materials are an important part of the cost, the fibre volume in ordinary applications such as, industrial floors and pavement, should not exceed 0,5% or be lower, while for demanding applications those value could go up to 3%. Above this last percentage are required special techniques. However, should be considered that high fibre volumes difficulties the correct distribution of the fibres.

4.5. MECHANICAL EVALUATION OF DOFS LIGHTWEIGHT CONCRETE SLABS

4.5.1. Introduction

According to the *European Project Group* [73] in the design of reinforced concrete sections, the bending tensile strength of the concrete is used for the evaluation of the cracking moment in prestressed elements, for the design of reinforcement to control crack width and spacing resulting from restrained early-age thermal contraction, for drawing moment-curvature diagrams, for the design of unreinforced concrete pavements and for fibre reinforced concrete [73].

Usually the concrete elements reinforced with steel subject to progressive bending forces till rupture (Figure 4.14) allow establishing 3 different stages [11]:

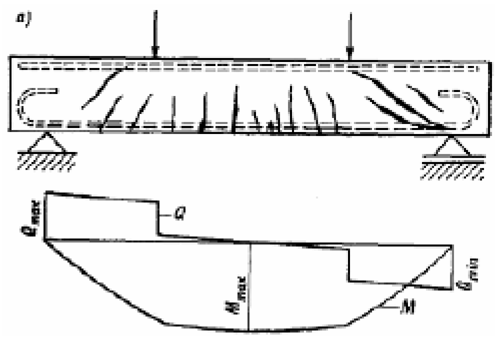


Figure 4.14 – Bending behaviour of steel reinforced concrete [11]

Stage I (Figure 4.15): under low mechanical solicitations, the concrete and steel reinforcement armours stresses are not very significant and their deformations are mostly elastic. The relation between deformations and stress is linear. With the increase of mechanical solicitations, deformations are produced and diagrams become curved while in the compression area the deformations remain in the elastic domain. An increase of the mechanical solicitations causes cracking of the concrete. A new stage begins.

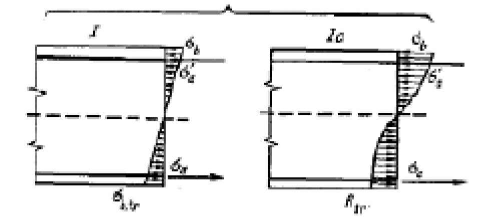


Figure 4.15 – Work stage I of beams subject to bending [11]

Stage II (Figure 4.16): In the cracks sections all the existing loads are absorbed by the steel armours. The concrete-steel adhesion remains intact between the cracks and, the concrete still contributes. Due to the raise on the mechanical solicitations, the stress in the area subject to compression, are intensified leading to the concrete creep and the stress diagrams become curved.. The smallest increase in the mechanical solicitations causes a quick crack opening in the tensile area, the stresses start to increase for constant solicitations and the element starts the rupture stage. A new stage begins.

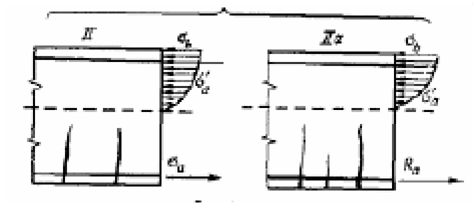


Figure 4.16 – Work stage II of beams subject to bending [11]

Stage III (Figure 4.17): This stage is characterized by intensive creep at the most part of the concrete in the area subject to compression, being the stress diagram curvature in this area much more pronounced. The rupture happens when the stress in the armours achieves its elasticity limit and the area subject to compression starts to disintegrate due to the consecutive deflections or, when the stress of the concrete subject to compression exceeds their rupture limit.

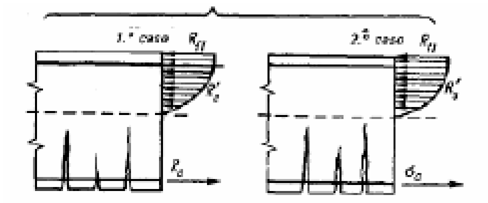


Figure 4.17 – Work stage III of beams subject to bending [11]

Fibrous materials (depending on the quantity and adhesion) modify the tensions distribution in the area subject to bending, leading to the displacement of the neutral axis for the compressed area. For high amount levels of fibres there is increase on the bending strength.

4.5.2. Bending tests

4.5.2.1. **Standard, equipment and procedure**

Three-point bending tests were carried out to evaluate the mechanical performance of the DOFS concrete slabs, according to EN 1339:2003, annex F European Standard [84]. The slabs dimensions were 30cm length, 15cm width and 4cm thickness. The distance used between the load bearing support and the edge of the flag was 25cm. Bending strength was determined, according to the following equation (4):

$$T = \frac{3 \times P \times L}{2 \times b \times t^2} \qquad \text{(Eq. 5)}$$

Where, ***T*** is the strength [MPa], ***P*** is the breaking load, [N], ***L*** is the distance apart from the supports [mm], ***b*** is the width of the slab [mm], and ***t*** is the thickness of the slab [mm]. Figure 4.18 shows DOFS reinforced concrete slabs under bending test.

The equipment used was a 50KN portico with a 25 KN serve-actuator controlled by SENTUR II at 10 µm/s of velocity.

Figure 4.18 – Bending tests on DOFS reinforced concrete slabs

4.5.2.2. Bending results and analysis

The DOFS reinforced self-compacting concrete slabs were identified using the following abbreviations, ***SCC DOFS***, meaning self-compacting concrete slab reinforced with a directionally oriented fibrous structure, followed by a number corresponding to the DOFS used. Regarding to the concrete slab without any type of reinforcement the abbreviation used was $\boldsymbol{SCC_{plain}}$ meaning plain self-compacting concrete slab, while for the steel reinforced slab the abbreviation used was $\boldsymbol{SCC_{steel}}$.

The average bending test results of DOFS reinforced concrete slabs, plain self-compacting concrete slabs and steel reinforced self-compacting concrete slabs are summarized in Table 4.8.

Table 4.8 – Reinforced and plain self-compacting concrete slabs bending results

Samples ID	***Breaking load (N)***	***Bending strength (MPa)***	***Strain***
SCC $DOFS_1$	3950	7,41	0,0021
SCC $DOFS_2$	3984	7,37	0,0020
SCC $DOFS_3$	3840	7,20	0,0017
SCC $DOFS_4$	4450	8,34	0,0020
SCC $DOFS_5$	4187	7,85	0,0025
SCC $DOFS_6$	4208	7,89	0,0019
SCC $DOFS_7$	4077	7,64	0,0016
SCC $DOFS_8$	3194	5,99	0,0022
SCC $DOFS_9$	3530	6,62	0,0018
SCC $DOFS_{10}$	4280	8,03	0,0035
SCC_{plain}	3216	6,03	0,0023
SCC_{steel}	7410	13,89	0,0110

Also it is possible to see in Table 4.9 the results grouped according to the main relations established previously in chapter III. In Group 1 and 2 the longitudinal reinforcement varies in terms of structural density while the transversal is constant. In Group 3 the linear density is the variable parameter in longitudinal direction keeping the transversal constant. In Group 4 and 5 the parameter structural density is the one which varies in transversal direction while the longitudinal is constant.

Table 4.9 – Bending results grouped according to the established relations

Group ID	***Samples ID***	***Fibres (%)***	***Breaking load (N)***	***Bending strength (MPa)***
1	SCC $DOFS_1$	0,08	3950	7,41
	SCC $DOFS_2$	0,13	3984	7,37
	SCC $DOFS_7$	0,22	4077	7,64
2	SCC $DOFS_1$	0,08	3950	7,41
	SCC $DOFS_3$	0,13	3840	7,20
	SCC $DOFS_4$	0,22	4450	8,34
3	SCC $DOFS_2$	0,13	3984	7,37
	SCC $DOFS_3$	0,13	3840	7,20
	SCC $DOFS_{10}$	0,13	4280	8,03
4	SCC $DOFS_5$	0,11	4187	7,85
	SCC $DOFS_3$	0,13	3840	7,20
	SCC $DOFS_8$	0,16	3194	5,99
5	SCC $DOFS_6$	0,11	4208	7,89
	SCC $DOFS_2$	0,13	3984	7,37
	SCC $DOFS_9$	0,16	3530	6,62

Analysing the Table 4.9, the SCC_{plain} slab and the SCC $DOFS_8$ present the lowest bending strength. It would be expected that the plain concrete present the lowest value of bending strength due to the absence of reinforcement. However, the SCC $DOFS_8$ presents the lowest value what could be explained by the use of different concrete. As was mentioned before the concrete features vary due to several parameters. The slab reinforced with steel (SCC_{steel}) presents the highest value as expected. Regarding to the directionally orientated fibrous structures, the one which presents the better bending performance is the slab reinforced with the $DOFS_4$. The samples reinforced with the fibrous structures present an higher bending performance when compared to the sample not reinforced (SCC_{plain}), so the DOFS reinforced concrete slabs improve the mechanical behaviour of concrete elements. However, they present lower performance to the steel reinforced concrete slab.

4.5.2.3. Bending behaviour

Figure 4.19 shows the typical curve behaviour for DOFS reinforced concrete (SCC $DOFS_4$), steel reinforced concrete slab (SCC_{steel}) and plain concrete slab (SCC_{plain}). In all samples it is possible to identify 3 different stages behaviour which are described as follows for each one.

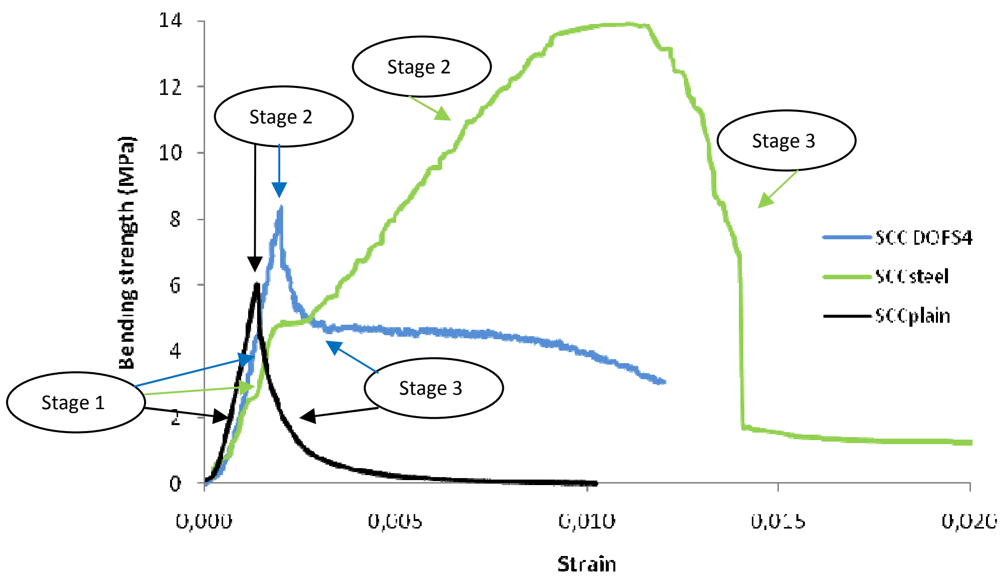


Figure 4.19 – Bending strength *vs* strain curve of steel reinforced slab (SCC_{steel}), DOFS reinforced slab (SCC $DOFS_4$) and unreinforced slab (SCC_{plain}).

Plain concrete slab

Stage I: at the initial stage the slab presents a linear behaviour supporting loads up to the maximum force;

Stage II: first cracks are formed and the bending strength is attained;

Stage III: after the concrete breaking the load bearing capacity decreases and strain increase till the complete failure; in this stage the unreinforced slab presents a low energy absorption capacity due to its weak bending behaviour and brittle failure.

DOFS reinforced concrete slab

Stage I: the slab presents a linear behaviour supporting loads up to the maximum force; corresponds to a short period where reinforced SCC has very low strain and the DOFS are not activated;
Stage II: characterized by the formation of the first cracks when the bending strength is reached; at this point the DOFS starts to carry the applied loads;
Stage III: no further cracks are formed and load carrying capacity decreases and the strain increases up to the complete rupture; when compared to the unreinforced concrete slab presents an higher energy absorption capacity.

Steel reinforced concrete slab

Stage I: the slab presents a linear behaviour up to the yielding point; from this point, plastic deformations take place;
Stage II: characterized by the load bearing capacity increase followed by structure deformation; bending strength is achieved;
Stage III: finally, failure occurs with an accentuated decrease of load bearing capacity.

Unreinforced slab presents a fragile material mechanical behaviour where the failure bending strength is the same as the maximum bending strength being the strain till the rupture lower when compared to ductile materials like steel. The steel reinforced concrete slab presents a mechanical behaviour similar to that of ductile materials where extensive plastic deformations occur before the rupture. Regarding to the DOFS reinforced concrete presents a similar ductile behaviour to the steel reinforced slab but with a better performance.

Regarding to the failure mode some differences in the type of the crack were observed in plain self-compacting concrete slab, steel reinforced concrete slab and DOFS reinforced concrete slabs. In plain concrete, when loads are applied crack is formed till the bending strength is achieved. Once the crack does not found resistance due to the absence of reinforcement the total collapse of the structure occurs (Figure 4.20).

Figure 4.20 – Plain self-compacting concrete slab crack

In the case of slabs reinforced by fibres, the fibres used delay the cracking. The crack becomes a progressive process once the transference bridges formed by the fibres, absorbed part of the solicitations leading to a more distributed microcracking. The fibres presence causes less cracks diminishing its area and restrained to a unique area. Figure 4.21 shows the crack opening in DOFS reinforced slab. Once the fibres present high modulus, the deformation and the cracking of the matrix are reduced once they are able to develop high bending strength with low strain. Thus, they improve the mechanical performance increasing the required energy for the structure collapse.

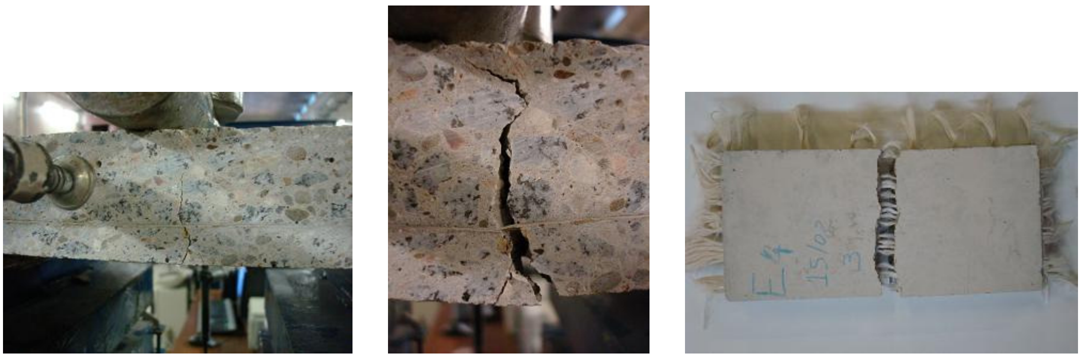


Figure 4.21 – DOFS reinforced self-compacting concrete slab crack

In Figure 4.22 is possible to observe steel reinforced slab. The cracking occurs in several areas of the slab being the cracks bigger than in the previous case. The damage caused is higher than in the DOFS reinforced crack.

Figure 4.22 – Steel reinforced self-compacting concrete slab crack

4.5.2.4. Influence of rovings linear density and structural density on slabs mechanical behaviour

In next sections the analysis of the relations established previously between the different DOFS, plain and steel self-compacting concrete is discussed.

A. Group 1 - Increase of structural density in longitudinal direction keeping the transversal direction constant

Figure 4.23 shows the mechanical behaviour for Group 1 (DOFS 1, 2, and 7) bending mechanical behaviour where structural density increases in longitudinal direction being constant the transversal direction. Slab SCC $DOFS_1$ presents the worst mechanical behaviour, due to the lower density of rovings as well as the amount of fibres (0,08%) in the slab therefore less filaments are supporting the loads applied. Slab SCC $DOFS_7$ shows a better mechanical performance once presents the highest rovings density in the direction of the applied loads. In this case the amount of fibres is much higher leading to better performance once the number of micro cracks intercepted by the fibres is higher. As expected, the higher is the fibre rovings density and the amount of fibres in the longitudinal direction the better is the composite performance.

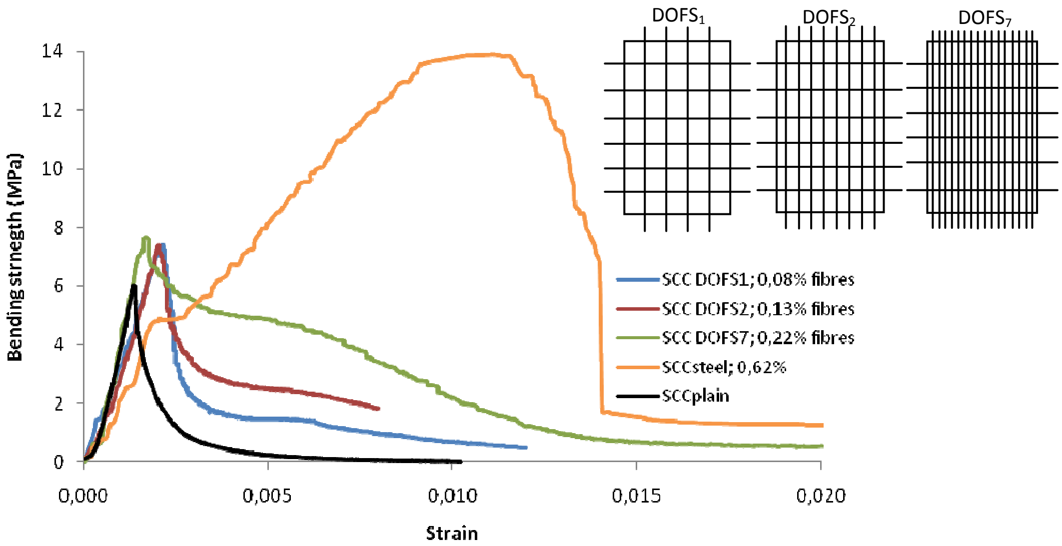


Figure 4.23 – Group 1 bending strength *vs* strain curve

As can be seen, these two parameters are influencing the energy absorption capability of the slab, as the area below the bending strength *vs* strain curve is varying in each slab. In order to establish the correlation between the slab energy absorption and the reinforcing rovings density, the energy absorption has been calculated for the whole set of slabs tested, at 0,08 of strain.

Analysing the results presented in Figure 4.24, it is possible to conclude that the energy absorption capability is directly proportional to the structural density of the reinforcing rovings in the slab. As can be seen, the correlation coefficient between structural density and energy absorption is very high (R^2 = 0,9984), which shows that the relationship between these two parameters may be established using a linear equation – Energy Absorption = 0,0041 Density + 0,0254. An increase in the rovings structural density is leading to an increase in energy absorption capability.

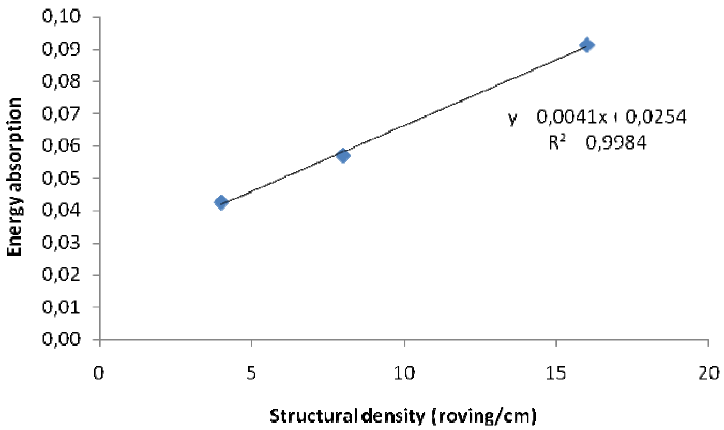


Figure 4.24 – Relation between structural density and the energy absorption on Group 1

B. Group 2 - Increase of linear density in longitudinal direction keeping the transversal direction constant

Group 2 (DOFS 1, 3, and 4) is characterized by the increase of linear density in the longitudinal reinforcement while that in the transversal is kept constant. Analysing the Figure 4.25 it is possible to conclude that slab SCC $DOFS_4$ is the sample presenting better mechanical behaviour when compared, to the others, once has an higher linear density (34080 Tex), i.e., each roving presents more filaments leading to an higher capability in supporting loads; sample SCC $DOFS_1$ shows the worst mechanical behaviour once presents less linear density (8520 Tex). Accordingly it seems that the linear density increase, besides working as a barrier to the cracking allows higher loads transference once fibres absorb a part of the loads creating a more distributed cracking. With increase on fibres number, the crack opening is lower and the total area of cracks is reduced. It seems that increasing the linear density in the longitudinal direction is improving the bending mechanical performance of the slab.

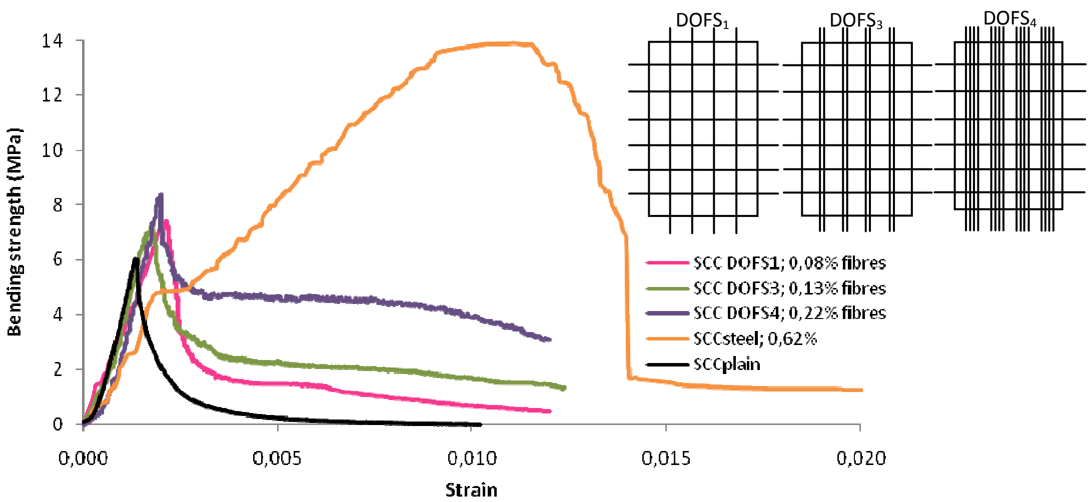


Figure 4.25 – Group 2 bending strength *vs* strain curve

The correlation between the linear density parameter and the slabs mechanical behaviour in terms of energy absorption was determined. Analysing the results presented in Figure 4.26, it is possible to conclude that the energy absorption capability is directly proportional to the linear density of the reinforcing rovings in the slab. As can be seen, the correlation coefficient between linear density and energy absorption is very high (R^2 = 0,994), which shows that the relationship between these two parameters may be established using a linear equation – Energy Absorption = $9E^{-06}$ Linear density + 0,0211. An increase in the rovings linear density is leading to an increase in energy absorption capability.

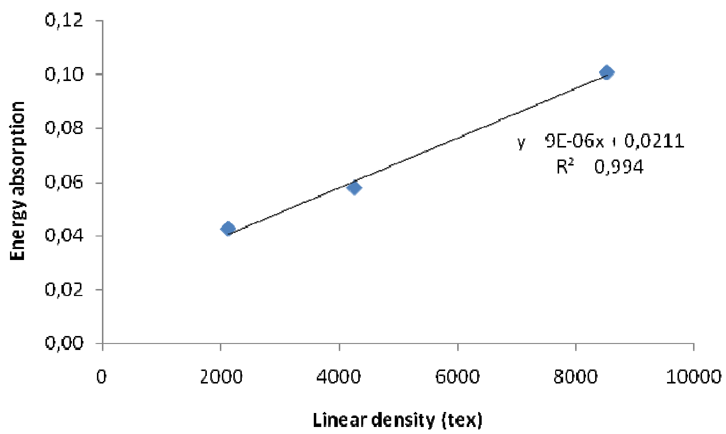


Figure 4.26 – Relation between linear density and the energy absorption on Group 2

C. Group 3 - Decrease of structural density in longitudinal direction keeping the transversal direction constant

Group 3 (DOFS 2, 3, and 10) were selected to study the influence of rovings distribution (structural density) along the reinforced element in longitudinal direction, maintaining the structural density in transversal direction. Analysing the Figure 4.27 the following conclusions may be established:

- SCC $DOFS_2$ slab and SCC $DOFS_3$ slab present similar mechanical behaviour so it seems although the sample reinforced with $DOFS_3$ structure presents a behaviour lightly superior;
- SCC $DOFS_{10}$ slab presents a different behaviour at the beginning of the bending strength *vs* strain curve, once it had developed higher values of bending strength for higher values of strain when compared to the other two samples.

Therefore it seems that the rovings distribution (structural density) does influence the slabs mechanical performance once the slab with lower longitudinal reinforcements presents a better performance. Thus, the rovings density decrease improves bending performance.

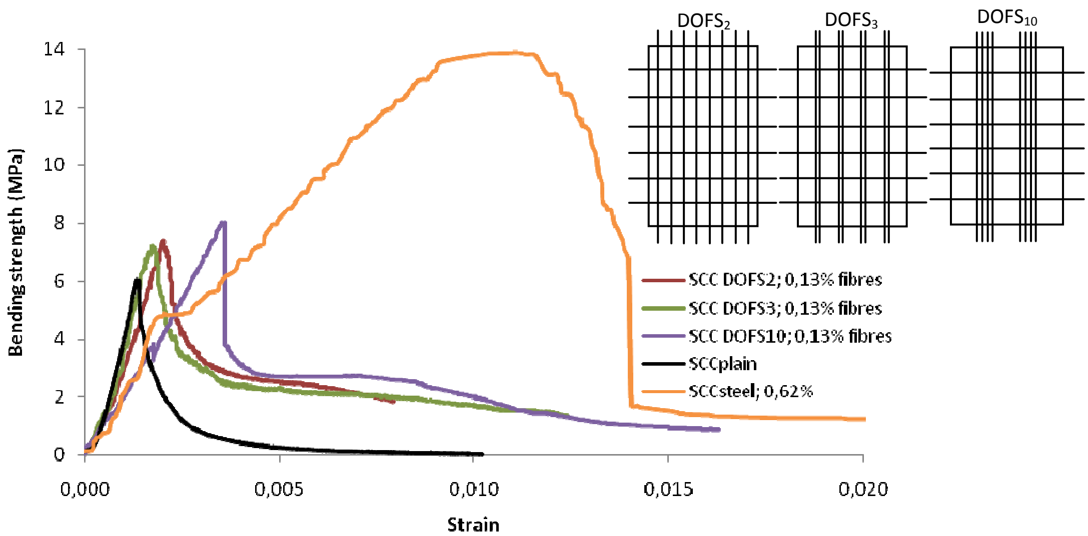


Figure 4.27 – Group 3 bending strength *vs* strain curve

The correlation between the structural density parameter and the slabs mechanical behaviour in terms of energy absorption was determined. Analysing the results presented in Figure 4.28 it is possible to establish in this case, a defined trend between both two parameters. However, as it can been seen the correlation coefficient is not very high (R^2 = 0,6352). Although, it seems to be a linear correlation, i.e., the lower is the structural density, the higher is the absorption energy capability. In this case, more samples should be tested to analyse the correlation established.

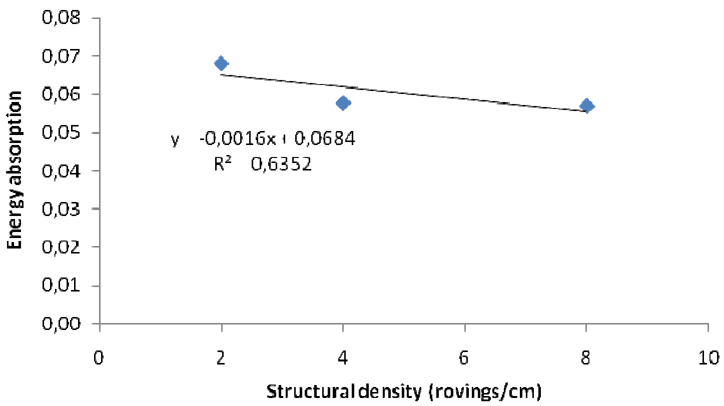


Figure 4.28 – Relation between linear density and the energy absorption on Group 3

D. Group 4 - Increase of structural density in direction transversal keeping the longitudinal direction constant

Figure 4.29 presents the bending mechanical performance for Group 4 (DOFS 5, 3, and 8) where the longitudinal reinforcement is kept constant and the structural density of transversal reinforcement is varied. Analysing the results it is possible to state that, sample SCC $DOFS_5$ with less density in the transversal reinforcement as well as in amount of fibres present in the slab, shows a better mechanical behaviour. The SCC $DOFS_8$ slab with 0,16% of fibres and with 12 transversal reinforcements, in terms of bending strength at rupture, presents a low value that could be explained by the concrete quality. Problems with their production or during the curing may be occurred, once it was not expected to be lower than the slab unreinforced (SCC_{plain}). The increase of rovings density in transversal direction has influence on bending mechanical performance.

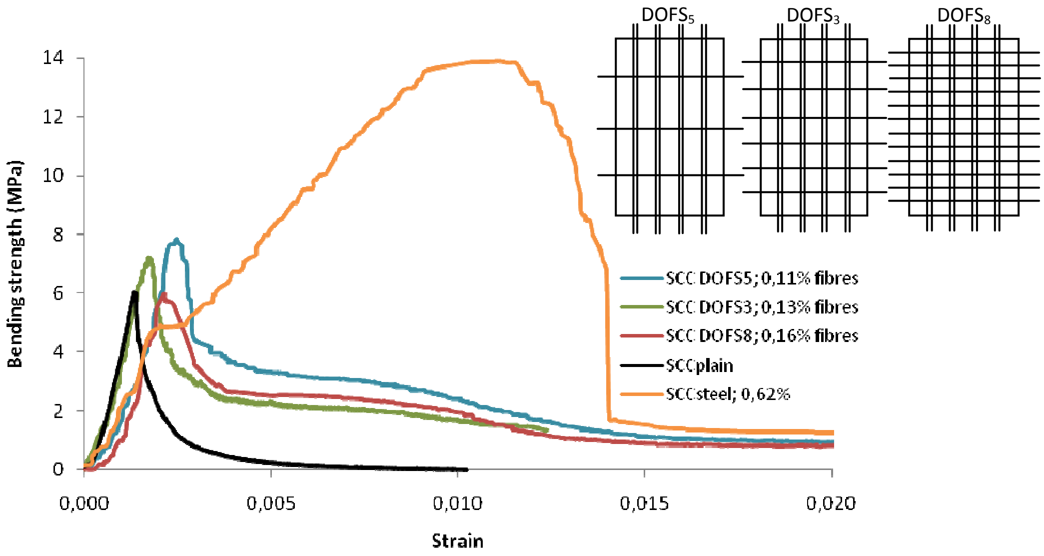


Figure 4.29 – Group 4 bending strength *vs* strain curve

The correlation between the structural density parameter and the slabs mechanical behaviour in terms of energy absorption was determined. Analysing the results presented in Figure 4.30 a linear decreasing trend may be observed. However, as it can been, seen the correlation coefficient is not very high (R^2 = 0,7). Although, it seems to be a linear correlation, i.e., the lower is the structural density, the higher is the absorption energy capability. In this case, more samples should be tested to analyse the correlation established.

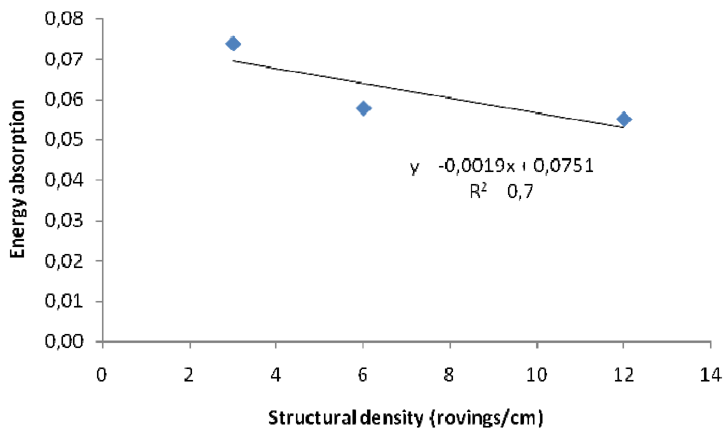


Figure 4.30 – Relation between linear density and the energy absorption on Group 4

E. Group 5 - Increase of structural density in direction transversal keeping the longitudinal direction constant

In Group 5 (DOFS 6, 2 and 9) is evaluated the influence of the density rovings decrease and their distribution along the reinforced element in transversal reinforcement, maintaining the longitudinal reinforcement. Analysing the Figure 4.31 it can be noticed that, sample SCC $DOFS_6$ characterized by less amount of fibres and with lower density of reinforcement in transversal direction, shows the best bending mechanical performance. The worst performance corresponds to the SCC $DOFS_9$ slab with the highest value of rovings density. This results point out that an high value of transversal reinforcements is not beneficial and does not improve and/or contribute to bending behaviour.

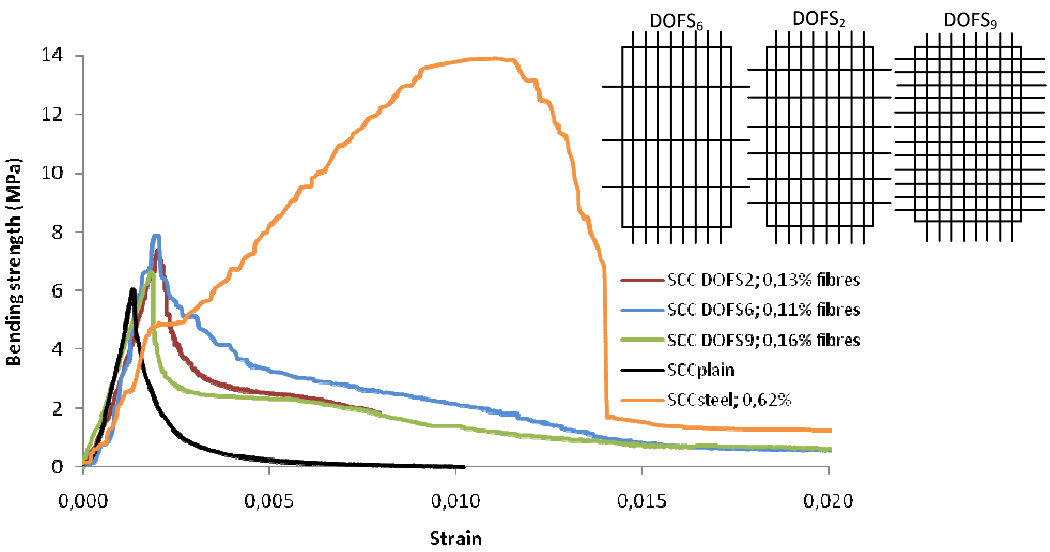


Figure 4.31 – Group 5 bending strength *vs* strain curve

The correlation between the structural density parameter and the slabs mechanical behaviour in terms of energy absorption was determined. Analysing the results presented in Figure 4.32 a clear trend on the variation between both parameters can be observed. However, due to the low correlation coefficient is not very high (R^2 = 0,7216) obtained it is no accurate to establish the linear relationship between both parameters by means of a linear equation. Although like in the previously group the trend seems to be the lower is the structural density, the higher is the absorption energy capability. Also in this case, more samples should be tested to analyse the correlation established.

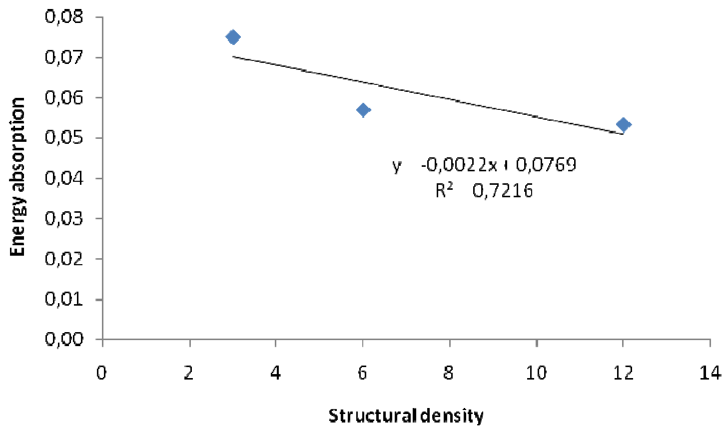


Figure 4.32 – Relation between linear density and the energy absorption on Group 5

E. Secondary established relations

Considering the Groups 4 and 5 where the longitudinal reinforcement is kept constant (8rovings/15cm) and the transversal reinforcement varies, it is noticed that, in both cases slabs with inferior density and less amount of fibres (SCC $DOFS_5$ and SCC $DOFS_6$) present better mechanical behaviour. Thus, it is possible to conclude that a reduction on the transversal reinforcement leads to a better mechanical performance.

Figure 4.33 shows the bending mechanical behaviour of secondary relations established previously. Regarding to SCC $DOFS_4$ *vs* SCC $DOFS_7$, although both samples present the same amount of fibres (0,22%) the increase of density in longitudinal direction does not have a significant influence in the mechanical properties of the slab once the behaviour is very similar. Comparing SCC $DOFS_4$ *vs* SCC $DOFS_{10}$, the decrease on rovings density in longitudinal direction influences the slab performance. The reduction on the number of reinforcements leads to a worst mechanical behaviour after the rupture, probably due to the lower percentage of fibres but presents a better performance at the beginning of the curve once the load necessary to cause the slab rupture occurs at higher strain.

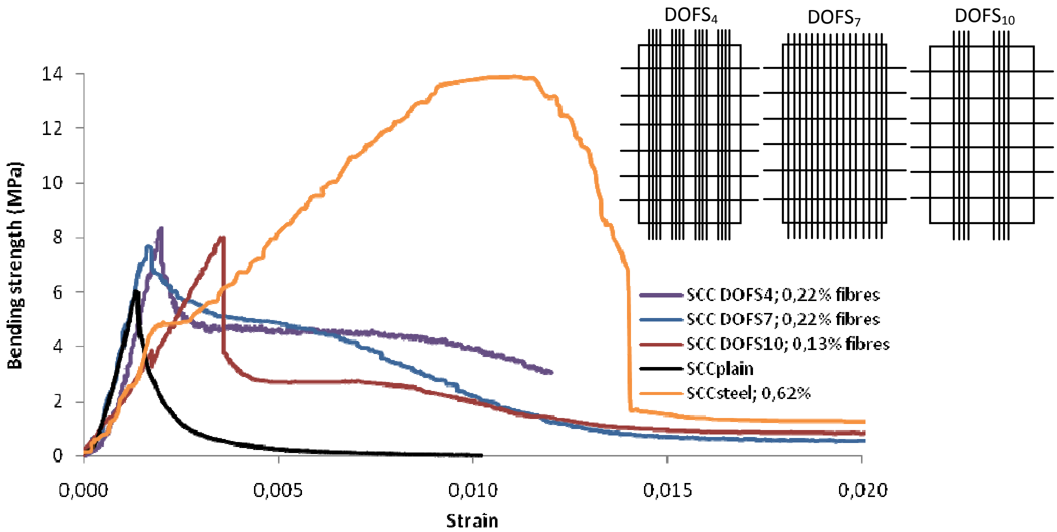


Figure 4.33 – Bending strength *vs* deflection curve of unreinforced slab and slabs reinforced with steel, $DOFS_4$, $DOFS_{7,}$ $DOFS_{10}$

Analysing Figure 4.34, it can been seen that the sample which presents less interesting bending behaviour is the unreinforced slab (SCC) due to the absence of reinforcement, and the one which presents better bending behaviour is effectively the slab reinforced with steel. Analysing slabs reinforced with directionally oriented fibrous structures, the SCC $DOFS_4$ and SCC $DOFS_7$, both with similar behaviour, are the samples which present better bending behaviour once they have the highest number of filaments in the load directions increasing the ability to carry higher tensile and bending loads, while the sample reinforced with $DOFS_1$ shows the worst behaviour due to the presence of less filaments. However, none of the slabs reinforced with fibrous structures present similar behaviour to that reinforced with steel. This fact could be explained by several reasons namely: DOFS reinforced slabs present less reinforcement percentage either in transversal and longitudinal directions when compared with steel reinforced slab which has 4 times more reinforcement; steel presents an higher modulus when compared to E-glass fibre; and the interface of steel-concrete is quite different from e-glass fibre-concrete, once steel has an higher modulus of elasticity the bond with concrete matrix is better.

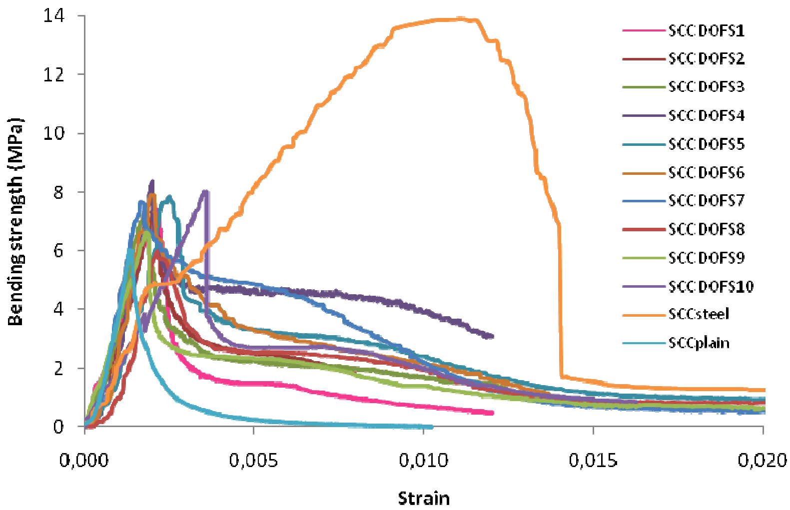


Figure 4.34 – Bending strength *vs* deflection curve of all concrete elements

CHAPTER V

CONCLUSIONS AND FURTHER WORK

5.1. GENERAL CONCLUSIONS

The research work undertaken aimed at the development of fibrous structures, namely directionally oriented fibrous structures (DOFS), as a concrete reinforcement material, being able to replace steel and overcome its main drawback – corrosion - having the suitable requirements to compete with steel in lightweight concrete elements reinforcement.

The work was developed in two distinct, but complementary stages. The first stage consisted in the directionally oriented fibrous structures (DOFS) development, characterization and production using an high-performance fibre, E-glass fibre. In the second stage, fibrous structures were applied as reinforcement in lightweight concrete slabs and mechanical bending tests were carried out in order to evaluate the mechanical performance of textile reinforced concrete slabs. Influence of rovings linear density (tex) and structural density (rovings/cm) on the mechanical behaviour of the reinforced concrete slabs has been studied.

A critic literature review on fibrous materials reinforced concrete and related subjects was done considering information on literature, internet, scientific journals, and research work done by universities. The literature survey performed, showed the interest by the research work undertaken as there are many issues to be understood so far the concrete reinforcement by fibrous structures is concerned. Within this literature survey was concluded that, in several issues, there are not at the moment consensus, namely regarding to the interactions between the cementitious matrix and fibrous materials reinforcement and improvement on toughness, ductility and strength. The basic mechanism regarding bond, durability and load carrying capacity are not yet understood in detail.

The basic woven fabric has been characterized in terms of weave structure, linear density, yarn count, mass per unit area and thickness. Mechanical behaviour of the basic fabric as well as the rovings used it has been also performed. Due to the difficulty to test glass fibre rovings and woven fabric under tensile, as they slip very easily, samples were prepared in a special way, i.e., impregnated with thermo-set resin at contact areas with both jaws. This enabled to perform tensile testing without slippage. The results obtained for both, roving and fabric show a large variety due to two main reasons: filaments damage and the impossibility to load all filaments at the same time during tests. As a consequence, the results obtained are lower than presented at literature.

Several directionally oriented fibrous structures (DOFS) were developed using a pre-stressing steel frame developed in order to stretch filaments and makes easier their placement during the casting. Self-compacting concrete was selected to produce the slabs once does not require vibration for placing and compaction, is able to flow under its own weight, fills completely the mould and restricted sections and hard to reach areas achieving full compaction, reduces and presents the same or higher engineering properties than the traditional vibrated concrete. A mould to produce the slabs has been also developed after several trial-errors experiments. Ten different DOFS presenting different longitudinal and transversal reinforcement in terms of linear density (tex) and structural density (roving/cm) were produced.

DOFS structures were used to produce self-compacting concrete slabs. After 28 days of curing bending tests were carried out on DOFS reinforced slabs, plain concrete slabs and steel concrete slabs.

Main conclusions to be taken include:

- as expected, the plain self-compacting concrete slab presented the worst behaviour due to the absence of reinforcement presenting very low energy absorption due to its weak bending behaviour and brittle failure while the steel reinforced self-compacting concrete slab presented the best bending behaviour;

- the directionally oriented fibrous structures (DOFS) improve the concrete elements bending behaviour;
- SCC $DOFS_4$ and SCC $DOFS_7$ present the best mechanical behaviour both with the same percentage of fibres (0,22%); the first one presents the highest linear density (34080 tex) in the load directions, and the second one the highest roving density (16rovings/15cm), which allows both to carry higher loads higher energy amount;
- SCC $DOFS_1$ presents the less interesting behaviour once presents the lowest linear density (8520 tex) in the load directions;
- either linear density and structural density has shown to have a significant influence on the reinforced concrete element mechanical behaviour;
- none of the DOFS reinforced concrete slabs present the same mechanical behaviour than that of steel reinforced self-compacting concrete slab;
- the higher is the structural density and the fibres amount in longitudinal direction, the better is the mechanical performance of the reinforced concrete;
- the higher is the linear density and the fibre amount in longitudinal direction, the better is the mechanical performance of the reinforced concrete;
- although it was not possible to establish a relationship between the reduction on the structural density and the mechanical behaviour of reinforced concrete with the same fibre amount in longitudinal direction, it seems that a decrease of rovings density leads to a better mechanical behaviour;
- although it was not possible to establish a relationship between the increase on the structural density and the mechanical behaviour of reinforced concrete with higher fibre amount in transversal direction it, seems that a increase of rovings density leads to a worst mechanical behaviour;
- the use of self-compacting concrete (SCC) presents several advantages namely, ability to flow, ability to freely pass through reinforcements and possibility on the production of thin and lightweight concrete elements.

5.2. FURTHER WORK

The development of the present research work enables to add some new interesting results to understand the use of fibrous materials as concrete reinforcement. However, some problems were encountered during its development and new ideas to be exploited may be studied in further research work on this topic.

In what concerns to the fibrous structures it is necessary to do a better characterization, mainly on the mechanical properties determination. An improved technique to determinate the tensile strength of woven fabric and rovings is needed. Also, when the fibrous structures are stretched in the pre-stressing frame it is not known what tension is given to the structure. The technique should be enhanced in order to apply the same tension to all structures. It could be also case of study the use of different types of high-performance fibres or the use of fibres combination such as glass-carbon fibres.

Further research work should also be performed in what concerns to concrete slabs production and to the improvement of the mechanical performance of fibrous structures reinforced concrete elements. The improvement of the fibrous structures reinforced concrete mechanical performance depends on the mechanical performance of the fibrous structure itself and on the fibrous structure reinforced concrete behaviour, namely in what concerns to the interface fibrous structure/concrete.

The basic mechanism regarding bond between fibrous materials and concrete is not yet understood in detail so far and during this work that was noticed. A more deeply study should be performed regarding to the bond nature between fibrous reinforcement and the cementitious matrix. The technique of pull-out test needs to be improved in order to obtain more reliable results.

With the present research work it is possible to open the door for the development of future research works that can lead to the development of directionally oriented fibrous structures (DOFS) to be used more efficiently as reinforcement material presenting the mechanical properties required to the final application.

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